THE SPATIAL AND TEMPORAL ANALYSIS OF FOREST RESOURCES AND INSTITUTIONS

Charles M. Schweik

Submitted to the faculty of the University Graduate School in
partial fulfillment of the requirements
for the degree
Doctor of Philosophy
in the School of Public and Environmental Affairs
and the Department of Political Science,
Indiana University

August 1998

UMI Number: 9907287

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

Accepted by the Graduate Faculty, Indiana University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Doctoral Committee:

Elinor Ostrom, Ph.D., Chair

Rosemary O'Leary, Ph.D.

J.C. Randolph, Ph.D.

John Williams, Ph.D.

Date of Oral Examination: August 21, 1998

ACKNOWLEDGMENTS

Without financial support, this dissertation could not have been written. The work in Nepal was supported by the Ford Foundation, New Delhi, India. The Indiana work was funded through the National Science Foundation (Grant # SBR-952-1918). The Dissertation Fellowship offered by the Workshop in Political Theory and Policy Analysis allowed me to concentrate on writing.

During my graduate years at Indiana University I have had the wonderful experience of working with not one, but three scholarly communities: 1) the graduate program in SPEA and Political Science; 2) the Workshop in Political Theory and Policy Analysis; and 3) the Center for the Study of Institutions, Population and Environmental Change (CIPEC). All three provided a stimulating intellectual environment for someone aspiring to become a scholar and teacher.

I am grateful to the SPEA and Political Science faculty who taught me during this program. I am thankful to Ph.D. director Larry Schroder and Karen Roberts for their efforts to help me through administrative and a couple tight financial times. In political science, John Williams taught me, among other things, to carefully think through statistical analyses and to critically question and understand what statistical software packages are doing. This critical concern I have found to be equally applicable as one works with remote sensing software. Rosemary O'Leary is a special and wonderful teacher, researcher, and a human being, who continues to inspire a community of graduate students. She has been a constant source of encouragement and sound thinking throughout my entire graduate career, and has been a mentor to me more than she probably realizes. J.C. Randolph provided an open office door from day one, and helped me significantly numerous times throughout my program. He was the one, for example, who suggested the important analysis I conduct in Chapter 5.

Kathryn Firmin-Sellers and Pat Sellers are wonderful friends and provided good ears at times when I needed it. Pat also provided a periodic escape from graduate school: a well paced tennis ball. I feel fortunate to be able to say I was a graduate school colleague with: Kevin Condit, Nives Dolsak, Jeff Ehman, Tom Koontz, Bill Littlefield, Aseem Prakash, Jennifer Turner, Paul Turner, and George Varughese. Beyond the scholarly considerations, each in their own way provided me with the important gifts of laughter and of friendship.

I am also deeply appreciative of the colleagues associated at the Workshop in Political Theory and Policy Analysis. The Workshop is a unique and special place of scholarship and community and it is staffed with incredibly helpful, patient, knowledgeable and capable people and each helped me at one time or another. But there are several people who helped me day in and day out with a constant cheerful demeanor and to them I am especially grateful: Patty Dalecki, Sharon Huckfeldt, Robin Humphrey, Linda Smith, Bob Lezotte, Paula Jerrells, and Mary Beth Wertime. I am also indebted to Vincent Ostrom not only as his role model of a true scholar but also for his generosity and friendship.

My association with the Workshop allowed me to grow significantly as an individual through opportunities to do research in Nepal. My experiences there have changed the way I view the world. My friend and colleague Kala Nidi Pandit once told me that the Nepalese consider "guests as god," and he and others certainly treated me that way. Special thanks go to Pandit, K.R. Adhikari, Ganesh Shivakoti, A.K. Shukla, Rajendra Shrestha, Mukunda Karmacharya, Vaskar Thapa and Sudil Gopal Acharya and the Institute of Agriculture and Animal Science in Rampur Chitwan for the assistance in the field research related to Chapter 2. I should also acknowledge the people living within the Kair Khola watershed, who so warmly welcomed me into their community and allowed us to study their area. To acknowledge these friends and their culture, I hope one day to follow the Nepalese tradition of planting two trees side by side as a community "rest stop" in my backyard with the hope that I can build as strong of a neighborly community as I saw in Nepal.

At this point I should also acknowledge the assistance of the Indiana State Forester. Burney Fisher and other members of his organization. Particularly Jim Allen, property manager of Morgan-Monroe and Yellowwood State Forest and Brenda Stein and others in his staff have been incredibly helpful throughout this research effort. Jim made available all his forest management records and was always ready to help or answer questions if we had any. Throughout my many days in his office and in the field, I was constantly impressed with the professionalism and care these public officials take in managing their property.

During my third year of my program, I was fortunate to get the opportunity to participate in the competition and award of an NSF grant that created CIPEC: an important new research center on the Human Dimensions of Environmental Change. This center brought together a large group of incredibly talented scholars from a number of disciplines. I have learned a tremendous amount through research projects and formal and informal discussions with Edwardo Brondizio, Laura Carlson, Cindy Croissant, David Dodds, Tom Evans, Derek Kauneckis, Clark Gibson, Tom Koontz, Bernie Slusher, Maria Silva-Forsberg, Jane Southworth, Catherine Tucker, and Steve McCracken. I appreciate Nancy Queen's efforts to be responsive to my administrative needs related to research projects, and Mary Buuck gave me excellent editorial assistance with a cheery smile. I appreciate the encouragement and confidence Emilio Moran has had and continues to have in me as a contributor to the Center's research. Given the significant technologies I have used in this dissertation, I must highlight the assistance Joby Jerrells and Julie England provided at every stage of my program. During my dissertation stage, Julie was like my "technical guardian angel" and a wonderful ally who always found a way to help me get past whatever technical hurdle was in my way.

The establishment of CIPEC provided me with the opportunity to work with Glen Green: a person with tremendous intellect and innovative capacity and a wonderful collaborative spirit. Glen, is an unwritten fifth committee member in this dissertation. He taught me remote sensing, and emphasized the importance of thinking carefully about how to link light reflectance to physical properties such as leaf morphology. Glen gave me guidance and a sounding board as I struggled on various technical projects vital to this dissertation. Glen inspired me with his ideas. And most importantly, Glen is a true friend.

My deepest appreciation, however, goes to Elinor Ostrom, who gave me initial funding to come to IU. It is impossible to express in words all that Lin has taught me. I certainly have learned a great deal from the theoretical, empirical and experimental work she has done and she has given me excellent advice throughout my program. Lin is also an exemplary dissertation chair. But in addition to these contributions, I have had the opportunity to work closely with her on several research grants and projects, and through this I have been able to learn much about how to run an effective research program and organization. Simply put, my collaboration with Lin has provided experience and insight that cannot be found in any class room. Finally, in the Workshop environment and beyond, Lin and Vincent practice what they preach: They provide examples of how each human should work to establish and maintain a warm, caring and nurturing community.

Members of my family have been especially supportive throughout these years in graduate school. Ron and Nancy Bushouse have provided wonderful rejuvenation retreats at their homes in Portage and Manestee, Michigan and have shown their love in so many ways they can't be listed. In addition, I am so lucky to have such caring, giving and supportive parents, who are willing at any time to drop everything they are doing to help me if I needed it. All my life, my father, Robert Schweik, has provided a strong example of how an academic can be both a great scholar and teacher. My mother provides not only another example of a scholar in her own right, but I think has passed on to me her own passion to explore new ideas and projects. Innovative ideas are crucial to projects like dissertations. And finally, I thank my colleague, companion, and soul mate, Brenda. Without her encouragement during some especially vulnerable times, I am not sure I would have made it through the program. She has a magical ability to say just the right thing at the times I need it most. And she keeps me cognizant of what is truly important. I am a much better and happier person with Brenda in my life.

Charles M. Schweik

THE SPATIAL AND TEMPORAL ANALYSIS OF FOREST RESOURCES AND INSTITUTIONS

This study addresses a central puzzle facing the Human Dimensions of Global Change research community: How can we understand the influence of environmental policies on human behavior when little or no information is available on the condition of forest resources? This dissertation capitalizes on new research tools, methods and approaches to overcome the "no information about the resource" problem. Specifically, I combine (1) forest mensuration techniques, (2) Global Positioning Systems, (3) Geographic Information Systems (GIS), (4) spatial statistics, (5) remote sensing, and (6) institutional analysis to analyze forest vegetation patterns. I provide explanation of these patterns by considering the incentive structures driving human decision-making and activity and do this through two studies in very different empirical settings.

Both studies apply applicable theory related to human behavior and action. Both examine the incentive structures individuals face as they undertake daily activities related to forest resources. The first study, set in East Chitwan, Nepal, identifies spatial patterns in georeferenced forest inventory data and links these to patterns predicted by optimal foraging subject to institutional constraints. The second study compares forest management in one state and one national forest in Indiana, U.S.A. In this effort, I identify spatio-temporal patterns in the forest vegetation captured by a time series of Landsat multispectral images. The combination of natural forest regrowth and property manager actions in response to incentives and constraints explain these patterns.

Substantively, both studies identify change in forest resources associated with combinations of the physical, human community and institutional "landscapes" in their regions. In both cases, geographic attributes of institutions (e.g., laws, rules) are found to influence the type and location of human actions. Methodologically, the two studies provide examples of how to control for natural influences carefully, and how to link theory on human behavior with spatial statistics, institutional analysis, GIS and remote sensing toward understanding human-environment relationships. By applying one of the two approaches outlined in the studies, a researcher can overcome the "no information on forest condition" problem in any empirical context.

Doctoral Committee:

Elinor Ostrom, Ph.D.

Rosemary O'Leary, Ph.D.

J.C. Randolph, Ph.D.

John Williams, Ph.D.

CONTENTS

Introduction

Study One

Study Two

Chapter 1

THE ANALYSIS OF NATURAL RESOURCE LANDSCAPES AND THEIR INSTITUTIONS

Introduction

On the most fundamental level, environmental policies are established to affect individual human behavior and action at a fine geographic scale[1] with the intent of changing outcomes or conditions in natural resources that exist at the same or broader (e.g., regional or global) scales.

For instance, a major component of the "global change" policy and research agenda—what many would consider the premier environmental issue of the 1980s and 1990s[2]—is to understand the relationship between human induced deforestation and afforestation at a fine geographic scale and levels of atmospheric concentrations of carbon dioxide (CO_2) measured at a global scale (Bouwman, 1990; Turner *et al.*, 1993; Keller *et al.* 1996; Brown, 1994). Turner and Meyer emphasize the importance of efforts to understand the fine scale human dimensions of global change when they state:

> Human actions rather than natural forces are the source of most contemporary change in the states and flows of the biosphere. Understanding these actions and the social forces that drive them is thus of crucial importance for understanding, modeling, and predicting global environmental change and for managing and responding to such change (1994:3).

The "Himalayan dilemma" provides a case of human action at a fine scale affecting a regional scale natural resource. The phrase refers to the relatively recent debate over the extent to which human-induced forest depletion in the Himalayan mountains has contributed to regional flooding along the Ganges river basin. While more recent research reports that a significant amount of the flooding is a result of "natural" weather-physiographic relationships (Ives and Messerelli, 1989), the question still exists over what degree human action on forest resources located far away contributes to the problem.

There are even difficulties when we study the effects of fine scale human action on what we might consider fine scale natural resources. Human-induced forest change often has a direct effect on a local ecosystem and thus on the humans that live proximate to that ecosystem. At a fine scale, the negative externalities caused by combinations of human action and natural disturbances on forests are more immediate, more apparent and perhaps, to individual human users of the resource, more "real." In many instances, human activities lead to natural resource consumption that is readily apparent to the people living adjacent or within the resource; many of these cases exemplify Hardin's (1968) famous "tragedy of the commons" and are most apparent at these local or fine geographic scales. These changes in forest conditions almost always produce some tension and community conflict over what is the appropriate use and management of this complex, multi-use resource (see for example Langston, 1995; Hinnefeld, 1996, 1997; Wilkinson and Anderson, 1985). Such changes may range from alterations of the aesthetics of surroundings, or some loss of personal privacy, to more drastic threats to the very means of subsistence of some or all members of the community. But, in any case, human actions almost always produce fine scale consequences on the condition of a natural resource.

However, not all changes in natural resource conditions are in response to direct human activity. Many non-anthropogenic influences occur at a fine geographic scale that also influence the structure and composition of a particular forest resource. "Naturally" occurring fine scale disturbances such as fire caused by lightning strikes, windthrows, wild animal grazing and variation in yearly weather can produce large changes to a forest resource (Spurr and Barnes, 1992).

Investigations that work to tease out the effects of direct human action from "natural forces" on natural resource change at a fine and regional scales are therefore of critical import to inform natural resource managers and others who make decisions related to policy that influences all geographic scales. But as Turner and Meyer's statement suggests, this is not enough. In order to formulate sound policies, regardless of whether it be at fine, regional or global scales, we must extend our efforts beyond an analysis of the direct human effects and undertake investigations that focus on the incentive structure—the underlying forces—that have produced various change in resource conditions (Turner, *et al.*, 1993:35; Naiman, *et al.* 1997).

This dissertation, therefore, analyzes human action and incentives related to the use of forest resources over time and at fine to regional scales.[3] The purpose of this endeavor is to contribute to the corpus of knowledge in the global change and environmental policy literature in two ways: first, by capitalizing on relatively new research tools, methods and approaches to the study of fine and regional scale forest change; and second, by tying theory related to human behavior and action to outcomes that are revealed in particular forest conditions. Specifically, this dissertation combines the use of (1) traditional forest mensuration techniques, (2) Geographic Information Systems (GIS), (3) spatial statistics, (4) more recent developments in remote sensing, and (5) institutional analysis to analyze patterns in geographic space and time, and to provide some explanation of these patterns by considering the incentive structures driving human decision-making and activity.

The Governance of Natural Resources: Human Actors as "Stewards"

Because human action is the major emphasis of this research, let me identify at the onset three categories of human actors, who, because of their decisions and/or actions, serve as "resource stewards" (Meffe and Carrol, 1994).

High-level decision-makers comprise one major category of forest stewards. These people develop and institute policy related to a natural resource. They rarely undertake direct actions upon the resource themselves, but often establish broad rules, conditions, and guidelines that other actors, such as property managers and forest users are either required or advised to follow. Actors in this category include high-level agency officials, judges, politicians in legislative bodies and decision-makers running private sector timber harvesting companies.

Second, there are those who undertake the daily operation and management of the forested area. These individuals may have as one of their tasks the responsibility to further refine management practices and use guidelines for others within or external to their organization. They also may be involved in the direct physical management of the particular forest resource. Actors in this category include (1) public sector or private company officials at the field level (such as property managers and their staffs) who oversee the direct actions that are undertaken on a particular forest resource, (2) private forest owners who make decisions and take actions related to its use and maintenance, and (3) associations of forest users in the community who meet to discuss and plan their own activities related to the operation and maintenance of a certain forested area.

I include in the third category other actors, the "general public," "the community" or special interest groups who utilize a forest resource and have an interest in the management of that resource. These either utilize the forest directly or participate in debates over existing or proposed policies. In some instances, members of this category can influence both the incentive structures that are developed and the direct human actions that are taken on the forest through the actions they take through public forums or judicial systems.

Institutions as StewardshipTools

Institutions are the means through which stewards set out to accomplish their goals related to forest governance and management. Institutions "simultaneously determine the rules of the game and condition the choices of individuals" subject to the rules (Miller, 1992: 9). Institutions exist at three levels.

At an operational level there are the mechanisms or "working rules" (Commons, 1959) crafted by human stewards in an attempt to alter the incentive structure of those who utilize the forest (E. Ostrom, 1990: 51). Operational level working rules prescribe what sets of direct actions individuals are permitted, required or prohibited to undertake in relation to the resource (E. Ostrom, 1986a; Crawford and E. Ostrom, 1995). They affect the daily decisions taken by actors involved in direct action affecting a resource, whether these actions be appropriation (harvesting) activities or production (improvement) activities. They may define where, when and how forest resources are utilized, how actions are monitored, and the sets of punishments and rewards associated with the variety of approved and prohibited activities (E. Ostrom, 1990: 52). Operational level institutions have the most direct and immediate effects on the condition of the forest resource by specifically altering the incentive structure of actors who utilize and maintain it.

But, operational level institutions do not simply exist; they have to be designed and established. Hence, a second and third level of institutions—what Kiser and E. Ostrom (1982) refer to as 'collective-choice' and 'constitutional choice' institutions—are also important to investigate to understand why humans make the choices they do in their actions related to a resource. Collective-choice rules influence operational activities by determining who is eligible and what mechanisms or procedures are used to change operational level rules. Constitutional-choice rules determine who is authorized to craft collective-choice rules, and define the process in which these rules are made (E. Ostrom, Gardner and Walker, 1994: 46). Constitutional and collective-choice rules indirectly influence the outcomes we witness in a forested area for they define the personnel and the mechanisms in which operational rules are constructed and modified.

Rules, whether they be at the operational level or higher, take on many forms that often directly reflect the type of actors that developed them. Rules may be well-enforced formal laws, put in place by national or state legislative bodies. They may be standard operating procedures or practices, developed by resource managers of a national, state or local organization or by a private firm. Rules may even be unwritten but well understood and accepted practices developed by members of the community that they affect, and may have evolved over time through many years of community interaction. The extent to which a particular institution is recognized, understood and agreed upon by individuals within the forest management and user communities is an important characteristic as to whether it may be considered a "working rule" (Knight, 1992; E. Ostrom, 1990; V. Ostrom, 1980, 1991).

Some formal laws may not be among the working rules simply because they are not recognized, understood and followed by the community affected.

In most if not all natural resource settings there will be combinations of (1) formal rules, (2) standard operating procedures and (3) well-understood but informal operational rules in existence. Moreover, in all cases, collective- and constitutional-choice mechanisms will be responsible for crafting these rules. Institutions are thus sets of hierarchical, embedded and overlapping *tools* that human natural resource stewards at various jurisdictional levels establish and maintain to govern and manage natural resources based on their underlying philosophies and values. And, importantly, like the forest resources they govern, *institutions often exhibit geographic characteristics* and they *change over time and geographic space.*

A Framework For Conceptualizing The Spatio-Temporal Dynamics of Natural Resource Systems

Natural resources such as forests, watersheds, irrigation systems or fisheries are, of course, geographic entities. Human utilization of these resources over time, coupled with natural, nonanthropogenic induced factors, produce spatial "dynamics" in these systems. Figure 1-1 provides a framework[4] useful for thinking about such spatio-temporally linked dynamics. It describes a ***process*** that occurs over a given time period and specified area on the earth and is applicable to any temporal and spatial scale.

Three elements are both inputs to and outputs of the process: (1) the attributes of the natural resource itself, including its physiographic and climatic setting; (2) the attributes of the community which utilize and manage the natural resource; and (3) the institutional arrangements established to govern the use of the natural resource. We often hear the term "landscape" applied to the study of the physical geographic space of a particular location. I find the more generalizable definition provided by Pickett and Cadenasso more useful in this context. They define a landscape as "an abstraction representing spatial heterogeneity at any [spatial] scale" (Pickett and Cadenasso, 1995: 332). Each of these three elements—physical resources, utilizing communities, and institutional arrangements—exhibit some level of spatial heterogeneity. I find it therefore useful to conceptualize them *each* as types of landscapes that overlay one another (Figure 1-1). Let me now turn to a more detailed explanation of what comprises each of these individual landscapes.

*** Figure 1-1 about here ***

The Physical Landscape

The physical landscape describes the current spatial distribution of the physical and biological features of a natural resource system at a given point in time. A forest physical landscape, for example, describes the spatial distribution of biotic and abiotic factors, with an emphasis upon woody species. Similarly, the physical landscape in an irrigation setting describes the various types of lining infrastructure, water flow levels, cropping patterns, and other physical components of the system. A physical landscape of a fishery may describe the geographic configuration of the shore and reef system, as well as the quantity and type of species that exist and are harvested in that particular area.

The Community Landscape

The community landscape represents the current spatial distribution of a bundle of variables which characterize attributes of the human population that utilize and manage a natural resource system. Socio-economic conditions, social norms of behavior, ethnicity, and other variables generally referred to as "culture" (Ostrom, Gardner and Walker, 1994: 45, Rockwell, 1994) all exhibit spatial characteristics. The location of human settlements and their associated attributes combine to create the community landscape that resides within and around the physical landscape of the natural resource system.

The Institutional Landscape

The importance of geographic or spatial properties and relationships related to physical world or community characteristics are well recognized. However, the idea that institutions or working rules also exhibit spatial characteristics is less often appreciated or considered. Often, in natural resource settings, rules—notably operational level rules—specify *location*. For instance, in forest settings, rules affecting the day-to-day decisions related to a resource will typically specify either (1) an area (e.g. "harvesting is prohibited in management unit one"), (2) an area and a species (e.g. "harvesting of *Shorea robusta* is prohibited in management unit one"), or (3) an area and a forest product (e.g. "harvesting of timber is prohibited in management unit one"). A fictitious example of geographic institutional boundaries such as property lines are shown in Figure 1-2, time period 1. Spatially configured rules have been identified in research related to other natural resources such as irrigation systems (see for example, Chambers, 1988; Ostrom, 1992; Tang, 1992; Shukla, *et al.* 1993) and fisheries (see for example, Schlager, 1990, 1994 and Berkes, 1992). For example, in an empirical study of inshore fisheries, Schlager (1994) discovered allocation rules that focus primarily on the location where fishing is allowed or forbidden rather than on the quantity of fish taken.

*** Figure 1-2 about here ***

Collective-choice and constitutional-choice rules also have geographic properties that are often closely tied to patterns of land ownership. The mechanisms in which operational rules are crafted--who determines what actions can or cannot be taken and the procedures that must be undertaken to modify these rules--may vary greatly depending on whether the particular natural resource is owned and managed by a national, state, private or communal organization. For example, federal agencies who manage forested areas in the United States are required to comply with collective-choice guidelines defined by legislation such as the National Environmental Policy Act (Clary, 1986: 179) while private forest owners or managers are not. Constitutional and collective-choice mechanisms also vary geographically over time, for land parcels are often bought and sold by private and public organizations.[5]

Incentives, Direct Human Actions and Outcomes

Over any given time period, the existing spatial configuration of each of these natural resource landscapes combine to create incentives and constraints on the current set of possible actions resource users and property managers can undertake (Figure 1-1, Arrow 1). This creates an "action arena" (E. Ostrom, Gardner and Walker, 1994)—a setting where actors consider alternative sets of resource related actions. These decisions are based on the incentives and constraints they face, coupled with their sets of preferences, information-processing capabilities, selection criteria and available resources (Ostrom, Gardner and Walker, 1994). The action arena is thus the setting in which humans decide upon what direct actions[6] they will undertake related to the resource landscape.

While actors certainly do not use these terms to characterize this decision, it is helpful to realize that there are two underlying questions that implicitly affect their actions: Which of the these three landscapes in Figure 1-1 will be modified? And at what location(s) should the chosen landscape(s) be modified? An example helps to explain this further. In a forest resource setting, a forest manager or forest protection committee may decide as their action to make an alteration in the structure of the forest institutional landscape. They may consider that an existing rule configuration may not be performing well or achieving its objectives and decide to modify the rule's requirements or modify the area that the rule governs. In another instance, a forest manager or user may decide that a direct action on the physical resource is appropriate; they may decide to harvest a particular stand at a particular location in the forested landscape or undertake some stand improvement activity (e.g. planting) at that particular location.

The strategic patterns of interactions of these individuals (Figure 1-1, Arrows 2, 3) (Tang, 1992) yield three types of outcomes[7]:

First, human actions produce modifications or imprints in the physical landscape (Thomas, 1956). As Pickett and Candenasso (1995: 333) put it: " There are very few [physical] landscapes that do not bear the contemporary, or historical but persistent, stamp of humankind." Even in old growth forest settings, evidence of previous human activity has been discovered (Keller, *et al.* 1996). Spatial choice decisions (Fotheringham and Rogerson, 1993) such as where to forage (Winterhalder, 1993), where to convert forest to agriculture (Thapa and Weber, 1990; Wolman and Fournier, 1987), where to harvest commercially valuable timber (Cleland, *et al.* 1994) or where to irrigate to plant rice (Chambers, 1988) are examples of strategic actions by actors that produce modifications or outcomes in the physical landscape.

Second, human actions produce modifications in the community landscape. Examples are abundant. Over a given period of time farmers may shift their location of residence, the community population may increase due to birth or migration, cultural changes may occur, and authority relationships may shift over geographic space. For instance, a farmer who resides at the tail-end of an irrigation system may be appointed to the water users' committee, thus altering the "spatial-balance" of the power structure between decision-makers. We might predict that in such instances, tail-ender problems may receive more attention by the committee in future time periods

Third, human actions may result in changes in the institutional landscape--modifications in the configuration of operational rules (see Ostrom, 1992; Ostrom, Gardner and Walker, 1994) that govern the natural resource. For example, in a community-owned forest setting, members of the governing committee may decide to prohibit harvesting in a portion of the forest that is particularly susceptible to significant levels of soil erosion. Similarly, in an irrigation setting, a particularly dry season may result in a decision by the water users committee to revise the existing water rotation scheme.

Indirect Forces, Non-Anthropogenic Actions and Outcomes

Direct human actions are not the only direct force behind change in the physical or community landscape of a natural resource. Non-anthropogenic disturbances also play a significant role in the change we witness over time in landscapes (Figure 1-1, Arrow 6). Some change we may witness in the physical landscape of a natural resource may be due to an exogenous shock, such as a seasonal weather change. We witness dramatic differences in deciduous forests between summer and winter seasons. Other less predictable "naturally" produced disturbance in a forest setting includes the following: fluctuations in weather patterns that go beyond typical seasonal variation (e.g. droughts, floods), violent storms (such as hail or tornadoes), fires that are the result of lightning strikes, and animal grazing.

Like human disturbances, many nonanthropogenic disturbances occur in specific locations within the landscape. The location where these "naturally produced" direct actions occur are in part determined by the indirect forces such as the topographic structure of the physical landscape (Figure 1-1, Arrow 4). Perhaps to a lesser degree, the structure of the community landscape also acts as an indirect force leading to nonanthropogenic action, in that locations of human communities alter the behavior of wild animals and hence their grazing patterns (Figure 1-1, Arrow 5).

To summarize, Figure 1-1 represents some arbitrary space over a defined period of time. At the beginning of this period, human actors consider the structures of the existing and overlapping physical, community and institutional landscapes when they take actions related to a natural resource. Given the geographic nature of natural resources, the actions taken by natural forces, and the combined consequence of actions taken by human actors over this period of time produce outcomes--changes in pattern--in any or all natural resource landscapes. These changes in natural resource landscapes provide feedback in the form of information to participating actors altering their incentive structures and thus behavior and the cycle begins again (Figure 1-1, Arrow 7).

The direct actions humans take are spatially configured and the temporal cycling of direct actions produce a spatially configured history for each landscape. This statement applies to each of the three landscapes, but let me use the institutional landscape to explain further. Any location within the boundaries of the landscape of interest may have been subject to a set of consistent and unchanging institutional arrangements or may have been subject to a variety of institutional changes over a given period of time (Figure 1-2). The temporal stability or variability of pattern we can identify in the physical landscape will be the result of human decision making and direct action on the physical landscape in response to indirect forces (the existing geographic configuration of three landscapes) coupled with natural direct action disturbance (e.g., weather effects) variability depicted by the process of Figure 1-1.

The distinction between direct actions and indirect forces is critical. The patterns we see in the physical resource are a result of direct actions. The study of natural resource change is a two fold process. We first must understand the patterns themselves and the past and present direct human and natural actions that have produced these patterns. We then need to follow this up with a deeper spatial and/or temporal analysis of the indirect forces—the spatial and temporal configurations of the three landscapes—in order to understand their geographic configurations and how they influenced the set of direct action choices (and their locations) made by human actors.

Efforts to Study Dynamics in Natural Resource Landscapes: A Brief Literature Review

One advantage of utilizing the general framework presented in Figure 1-1 to organize my inquiry is that it provides great flexibility when working in a multidisciplinary fashion and with a large number of variables (Ostrom, 1995b). In doing so, I have drawn upon the work of scholars in a variety of disciplines who have studied one or more of the components represented in this framework. Here I wish to review that research background, not, of course, to provide a comprehensive review of all possibly relevant literature—too many disciplines have been involved in related work—but rather to provide a general overview of work particularly applicable to my project, and, also, to point to what directions future applicable research should proceed.

A large proportion of recent applicable natural resource research has concentrated on how best to quantify the condition of a natural resource landscape. Many scholars from a variety of disciplines (e.g., ecology, anthropology, geography) have turned to satellite remote sensing and aerial photography to assist in land-cover inventory and quantification (Townshend and Tucker, 1984; Malingreau and Tucker, 1987; Justice *et al.* 1985; Woodwell, 1986; Trotter, 1991; Moran, 1994a, 1994b; Green and Sussman, 1990). These types of studies reveal the great value, as well as the difficulties, in using remotely sensed imagery when investigating change in the condition of the physical landscape of a natural resource. One of the great challenges in the field of remote sensing has been to understand what the digital numbers transmitted by satellite platforms represent (Justice *et al.*, 1985; Everitt and Richardson, 1987; Barrett and Curtis, 1992; Verbyla, 1995; Green, Schweik and Hanson, 1998). Similar efforts have been undertaken in the field of aerial photo interpretation (Sayn-Wittgenstein, 1961; Paine, 1981; Avery and Berlin, 1992; Gilruth and Hutchinson, 1990). The results of these efforts have been promising; we are beginning to develop a basic understanding of how to interpret different land cover types on images taken by a variety of photographic platforms of various locations on the earth. Green and Sussman (1990), for example, have utilized satellite images to monitor rates of deforestation in Madagascar. Moran *et al.* (1994a, 1994b) have been able to accurately identify forests of various stages of succession in the Brazilian Amazon using Landsat Thematic Mapper (TM) imagery. Similar efforts have been undertaken by Millette and colleagues (1995), who extended the use of remote sensing to capture components related to the structure of the community landscape. They employ digital image analysis to classify land-cover variables related to socioeconomic indicators and report that such attempts are scale dependent and that broad classification schemes in Landsat TM scenes can be, to some degree, useful in understanding the economic landscape of a particular location.

Landscape ecologists--many of whom are users of remotely sensed images as well--strive "to understand the ecological function of large areas and [stress] that the spatial arrangement of ecosystems, habitats, or communities has ecological implications" (Turner, 1990:21). They are particularly interested in studying the effects of pattern—e.g., patch shape, boundaries, edges, corridors, and mosaics in the physical landscape (Dunn *et al.*, 1991; McGarigal and Marks, 1994; Forman, 1995). These patterns influence important ecological processes such as animal and vegetation species distribution (Van Dorp and Opdam, 1987; Fahrig and Paloheimo, 1988), nutrient flow (Peterjohn and Correll, 1984; Ryszkowski and Kedziora, 1987) and net primary production (Turner, 1987). These landscape ecologists along with geographers and others have been active in developing and applying various analytical and statistical techniques toward identifying, understanding and predicting physical landscape patterns (Turner and Gardner, 1991; Moss and Davis, 1994; Dunn *et al.*, 1991; Arlinghaus, 1995; Shaw and Wheeler, 1994; McGrew and Monroe, 1993) and working to develop new methods using Geographic Information Systems (Fotheringham and Rogerson, 1994; Johnson, 1990; Kienast, 1993; Gastellu-Etchegorry and Sinulingga, 1988). The efforts made by scholars employing tools of remote sensing and landscape ecology are relatively new but already provide a library of mechanisms and approaches that can be used to quantify the condition of the physical landscape at broader scales.

While landscape metrics are a relatively recent development for quantifying landscape condition, other field level measures have been in existence for a longer period of time. Plot mensuration methods are commonly-used procedures that have been applied in the study of land vegetation, soil fauna, and aquatic environments (Brower, *et al.* 1997). A wide range of plot sampling techniques have been developed (see for example, Barbour, *et al.* 1987), and there are a variety of measures (e.g., frequency, dominance, density, and diversity indices) one can utilize to quantify the forest or other environment once the plots have been collected in the field (Brower, *et al.* 1997; Barbour, 1987; Randolph, 1993). These types of methods are commonly employed over a small area such as a few square kilometers (see for example Becker *et al.*, 1995; Dale *et al.* 1990) however there have been some efforts that utilize larger plots[8].

As efforts to quantify both physical landscape conditions and change have progressed, many other scholars have turned their efforts toward understanding the underlying variables or the indirect forces that have led to actions that produce these changes. Many of these studies focus specifically on variables that can be categorized as a component of the community landscape. For instance, scholars have investigated the influence of variables such as population growth (Rowe, Sharma and Browder, 1992; Abernathy, 1993; Pimental *et al* 1994), agriculture and livelihood practices (Shrestha, 1993; Metz, 1990; Meyers, 1988), access to markets (Poffenberger, 1990; Grainger, 1993), human migration and encroachment (Myers, 1994), community heterogeneity or homogeneity (Hackett, Schlager and Walker, 1994) and social norms and culture (Rockwell, 1994; Unruth, 1994) on the physical condition of the resource. Community variables such as these have been reported to be underlying causes of physical landscape change such as deforestation (Turner, 1996), water resource depletion (e.g., Bloomquist, 1992, Chambers, 1988; Tang, 1992; Lam, 1994), and fish stock depletion (Schlager, 1990)

A majority of these community landscape studies have been aspatial in nature; they do not include accurate geographic data in their analysis This is primarily the case because either geographic relationships were not deemed important for the research question at hand, or because accurate location data was not available or was simply too difficult (e.g. costly or time consuming) to work with and analyze. However, some scholars, especially in disciplines such as geography, demography, and remote sensing have worked diligently to gather location attributes and have greatly advanced our ability to study the influence of location on other dependent variables. These disciplines have focused most often on physical or community variables or have studied relationships between the two. Fox *et al.* (1995), for example, applied aerial photograph analysis to several watersheds to quantify changes in closed-canopy forests. Through this quantification of forest pattern and change over time, Fox and his colleagues revealed that the current day forest physical landscape is influenced by physical and biological factors, as well as by past and present social and economic parameters. Similar analyses involving physical and community landscapes have been conducted by Thapa and Weber (1990), Fox *et al.* (1994) and Gilruth *et al.* (1990).[9] Chomitz and Gray (1995) recently developed a spatially explicit model of land use in Belize that takes into account economic factors such as market accessibility via road infrastructure and report a strong relationship between agriculture use and market access The advances and availability of Geographic Information Systems and remote sensing technologies (Starr and Estes, 1990; Fotheringham and Rogerson, 1994; Wilkie and Finn, 1996) has led to a dramatic increase in physical or physical-community landscape studies (Stringer *et al.*, 1988; Lee and Marsh, 1995; Sader, 1995). However, in this set of literature, attention to the spatial attributes of natural resource institutions--the institutional landscape--has been largely been ignored.

A growing number of scholars have become interested in understanding how the institutional landscape alters human incentives related to the utilization of natural resources (Ostrom, 1990; Ostrom, Gardner and Walker, 1994; Schlager, 1990; Tang, 1992; Lam, 1994; Agrawal, 1995, Repetto, 1988). These studies are important for they turn attention more specifically to an analysis of the third landscape: the design, development and maintenance of institutions. Institutions have the potential to mediate the effects of physical and community landscape variables by altering the incentive structure of actors associated with a particular natural resource system (E. Ostrom, 1990; Agrawal and Yadama, 1997).

Much of the existing institutionally related research is cognizant of or has identified linkages between geographic relationships in institutional design and the dynamics of natural resource settings. For example, studies related to irrigation systems have discovered what can be intricate and carefully constructed water allocation rules that specifically state where (and when) water can be appropriated from the system (Chambers, 1988; Ostrom, 1992; Tang, 1992; Shukla *et al.*, 1993; Lam, 1994). Many of these efforts account for location by including a "head-end," "middle" and "tail-end" variable in their analysis. Similarly, in an empirical study of inshore fisheries, Schlager (1994) discovered that allocation rules were developed that specify the locations where fishing is allowed or forbidden instead of setting limits on the quantity of fish any given fisher can appropriate. Location specific rules are also reported in a fishery study by Berkes (1992). Recently, in an empirical study of watershed land-cover change, Schweik, *et al.* (1997) report that differences in the physical landscape of two adjacent sub-basins dramatically influence human response to similar institutional landscape structure. These studies suggest that geographic relationships exist in the institutional structure of a setting. This institutional geography influence patterns of human activity, leading to changes we witness in the physical landscape of a natural resource.

Information And Knowledge Gaps

These multidisciplinary efforts provide important foundations for this dissertation. They either establish theoretical, experimental or empirical support for the relationships depicted in Figure 1-1, or they render valuable insight into analytic or methodological approaches to the study of natural resource landscapes. However, despite this vast library of work, there still remains significant information and knowledge gaps that hamper our understanding of human behavior and action related to natural resources and how these actions influence natural resource condition and change.

Information gaps

There are three types of information gaps that are frequently encountered in efforts to understand dynamics in natural resource landscapes.

> *Information Gap 1: In a majority of circumstances, we lack baseline inventory data on the condition of the natural resource. In cases where such data exists, it is either not georeferenced, or it is georeferenced in an aggregate form.*

In natural resource settings, it often is the case that no inventory on the general condition of the resource has ever been collected. This is typically the case, for example, when a researcher is studying a forested area in a country that has few resources available for inventory activities as part of their forest management. In other circumstances, often where some professional staff has been managing a property for a period of time, past resource inventory data may be available. In forest settings, this type of data will typically have been taken at scattered intervals and locations over time (e.g., just prior to a stand's timber harvest). For the researcher interested in quantifying change in a resource these types of data can provide great utility; however, they often are supplied in some geographically aggregated form and do not cover the entire forested landscape for the given period of time. This limits the types of geographic analyses a researcher may be able to undertake with given sets of existing data.

When we wish to investigate questions related to natural resource *change*, the possession of inventory data from one point and time is not sufficient. The analysis of change requires either a temporal dataset on natural resource condition or at the very least very fine- or large-scale georeferenced data for one point in time.[10]

Information Gap 2: In most circumstances, we lack longitudinal, georeferenced data on natural resource condition.

In situations where resource condition inventory data does exist, it usually exists for one point in time only. It is here, in the collection of *georeferenced, longitudinal* data on the physical landscape of a natural resource, where remote sensing has become extremely useful. Aerial photo and satellite platforms have been utilized by many agencies in the U.S. and elsewhere for mapping, military and research purposes. Depending on the remote sensing platform and location of interest, image datasets may be available from these agencies that are geographically referenced and that have been taken repeatedly over varying time scales (Wilkie and Finn, 1996, Campbell, 1996). The problem in these instances, like the problem in inventory plots taken in the field, is one of cost and effort. Satellite images such as Landsat TM scenes are quite costly[11] and require significant processing equipment and technical expertise. Aerial photographs are usually less costly to acquire, but they typically are taken at a finer spatial scale that requires more processing and resources to construct an interpreted mosaic for landscapes covering a broad geographic area. For these reasons, longitudinal studies that utilize these types of platforms have not been readily undertaken.[12]

Even in the instances where we are fortunate enough to possess longitudinal data on resource condition that is geographically referenced, we still lack needed information.

Information Gap 3: In nearly all circumstances, we lack longitudinal, georeferenced data about the <u>institutions</u> that have governed the natural resource.

This is not to say that these data do not exist--they often do. But, depending on the type of natural resource being investigated and the organization(s) who have managed it over time, this data may be difficult to locate and formulate in a manner that is analyzable. These gaps in our information hinder our ability to analyze the effects of actions taken by the stewards associated with that resource.

Knowledge gaps

In addition to and in part due to these information gaps, we also possess "knowledge gaps"-- gaps in our theoretical understanding of the factors driving natural resource change.

Knowledge Gap 1: We possess an incomplete understanding of the longer term effects that direct human action has on natural resource condition.

As illustrated earlier in Figure 1-1, the change we witness in the condition of a natural resource is a direct product of two dynamic forces: naturally occurring disturbances and direct human action. While we possess large bodies of theoretical literature on forest ecological processes (e.g., Spurr and Barnes, 1992) and the effects of human management practices on forests (see for example the classic silviculture text by Smith, 1962), there is still much we do not know in regard to the cumulative effects of changing influences over time on natural resource condition. For example, some forested areas residing in publicly managed property may be subject to a policy change that could result in a change in the way people treat a particular forested landscape, but we very often do not know what the cumulative effects of changing (or for that matter stable) direct human actions have had on forested landscapes.

> *Knowledge Gap 2: We lack knowledge on variables that act as indirect forces that lead to changes in natural resource landscapes.*

Despite the tremendous effort given to the study of variables associated with the deforestation process--variables such as population growth, market access, macro-political forces, and institutions--little consensus on the relationships of sets of variables on the dependent variable has been achieved (Turner, 1995). Much less emphasis has been given, and therefore less theoretically is known, about the variables that have been influential in altering patterns of human action that then lead to large afforested areas such as the ones that now exist in the Midwest United States. Gaps such as these in our knowledge are to a large degree due to the complex interactions of variables associated within natural resource landscapes (Figure 1-1). Even the information provided in "simple" static and aspatial natural resource landscape data are tremendously complex and intertwined. Researchers who utilize these types of datasets have to take into account large sets of physical, community and institutional variables and be concerned with the validity of their findings in lieu of potential problems of simultaneity and interaction effects (see for example, Kennedy, 1994).

Knowledge gaps exist not only in the understanding how variables interact, but also in technical or methodological issues related to how we study such processes. Scale is one such technical area that seriously impedes our understanding in a wide variety of disciplines and research efforts.

Knowledge Gap 3: We lack understanding about how changing scale influences our findings related to human action and natural resource landscapes.

In the study of human-environment relationships, scale effects muddle our efforts to organize and compare the results of these studies in some consistent fashion. Scales at which data are collected vary between research efforts and organizations. This complicates data integration (Root and Schneider, 1995). For example, data collected and managed by a forest agency may be stored at a spatial scale that meets their managerial needs but is not appropriate for linkage to other available data sources such as satellite images.

Moreover, even though many natural resource analyses are to a large degree aspatial in nature--that is, they do not analyze the pattern of their data over geographic space--they are still very much subject to the effects of spatial scale. For instance, two identical analyses, one utilizing data aggregated at a village level and another conducted using data aggregated to a county level could easily arrive at quite different conclusions.[13] The approach most often used in ecological studies to overcome the effects of scale is to design a sampling strategy based on the known spatio-temporal characteristics of the process (Turner, *et al.*, 1989: 250). However, in instances where we lack knowledge related to the effects of scale, it is necessary to sample processes at several scales if at all possible (Turner, *et al.*, 1989; Root and Schneider, 1995). In cases where data is simply unavailable to undertake a multi-scale analysis, the researcher must still be extremely cognizant of scale effects and make every effort to understand them in the context of the research being undertaken.

Another serious knowledge-methodological gap related to human-environment type research is related to the use of remote sensing technologies. While satellite-based sensors hold great promise as information sources on geographic change of natural resources over time, we do not fully understand the information they provide.

> *Knowledge Gap 4: We do not adequately understand the relationships between the information provided by satellite images and the landcover on the ground. Moreover, we do not have well worked out methods for applying satellite imagery to study the human dimensions of environmental change.*

For example, vegetation indices such as the popular normalized difference vegetation index (NDVI) appear to be influenced both by leaf area and leaf morphology, but little is known about the influence of the latter (Green, 1996) Other more recent analytic techniques that supply methods of quantifying landscape condition, such as spectral mixture analysis (Adams, *et al.*, 1994) haven't been adequately explored as indicators of human driven pattern in natural resource landscapes.

More fundamentally, questions still exist that must be answered if we are to monitor human activities related to natural resources using remote sensing technologies. It is clear that these tools, at their level of resolution, are appropriate for monitoring change in general land classifications. But are these tools even appropriate for monitoring and analyzing the often more fine scale direct human forest management activities in various types of forests (e.g., temperate zone deciduous forests)? That is, do they provide enough information at their given level of resolution to identify the patterns that are the result of these practices? Some researchers have explored the use of these technologies toward the study of forest vegetation classification and change (e.g., Green and Sussman, 1990;

Moran, *et al.* 1994a, 1994b; Wolter, *et al.* 1995; Sader, 1995), but few have utilized these technologies to investigate the impact of fine scale management practices on the resource. Even less effort has been given toward linking what these data tell us with information related to the incentive structures and human motivations on the ground.

Opportunities And Objectives of This Study

These information and knowledge gaps create tremendous barriers to our understanding of the forces and processes that lead to change in natural resource landscapes. However, recent analytic, methodological and technological advances provide opportunities to extract new information from existing data about the influence of human activity on natural resource condition and understand the motivations behind these actions. These new approaches and techniques allow us to tease out more information about human activity from patterns in the natural resource—patterns that exist either in one point in time (geographic space only) or that exist in geographically linked longitudinal data (spatio-temporal space).

The Informing Potential of Spatial Analysis

In the instances where geographically-related data exists, but only for one point in time, a focus on the spatial patterns in the existing resource may be informative. The analysis of patterns in geographic space—the employment of techniques such as spatial statistics (Arlinghaus, 1995; McGrew and Monroe, 1993; Shaw and Wheeler, 1994)—can be harnessed to help identify "human activity patterns or imprints" that often exist in the physical landscape of a natural resource (Thomas, 1956; Pickett and Candenasso, 1995). An exploration of these patterns in geographic space can provide additional evidence which, when coupled with other archived or human memory information, can help the analyst piece the historical puzzle together much like the way detectives piece together evidence and witness testimony to solve a crime.

The Informing Potential of Longitudinal Remote Sensing Data

The availability of remote sensing data from satellite platforms provides an invaluable spatio-temporal dataset covering nearly the entire globe and dating back nearly a quarter of a century. For nearly all locations on earth, there exist a relatively large set (e.g., greater than 50) of geographically referenced, temporal multi-spectral image data. This fact, coupled with the advances we have witnessed in the computational power and storage of desktop computers and workstations, present the opportunity to process multiple satellite images and analyze them for temporal or spatio-temporal patterns. Through careful selection and processing of these temporal images, coupling the information they provide with topographic information and institutional data the potential is there for us to separate out the effects of the "natural forces" from human activity on the physical landscape of a natural resource.

Objectives

The objectives of this study can therefore be considered two-pronged. The first objective is to develop and refine analytic methodologies related to the analysis of natural resource landscapes. Toward this end, this dissertation combines various methodological tools and analytic techniques such as global positioning systems (GPS), GIS, spatial statistics, remote sensing, and spectral mixture analysis to measure and analyze patterns in the physical condition of a natural resource landscape. It links these tools with techniques and analytic approaches used to understand human incentives and motivations, what many refer to as "institutional analysis" (see Ostrom, 1990: 55). Methodological (M) questions to be answered related to this objective include the following:

M1) *How can we apply spatial analysis to extract additional information about change from a geographically referenced dataset that exists for only one point in time?*

M2) *To what degree can longer temporal extent Landsat data help in understanding change in forested landscapes over time?*

M3) *How can we tease out the effects of human activities from patterns in temporal sets of satellite imagery?*

M4) *To what degree does the analytic technique spectral mixture analysis (Adams et al., 1994) help to understand change that is captured by relatively course resolution MSS imagery?*

The second objective of this dissertation is empirical in nature. I intend to focus my analysis on two distinct settings, one in a developing world context and one in the United States, to explore the following general empirical (E) questions:

E1) *Where has change occurred in the physical landscape of the natural resource and where has it remained stable? And how are these linked to important policy issues?*

E2) *What direct human actions have taken place over time that have contributed to the change we witness in the physical landscape of natural resources?*

E3) *What are the indirect forces—the configurations of community and institutional landscape attributes—that have led humans to undertake these activities?*

E4) *What temporal patterns in the community and institutional landscapes appear to have led to resource conditions we might consider as "positive" or "negative"?*

In short, this dissertation capitalizes on new approaches and techniques to understand the direct and indirect forces that yield change in the physical landscape of forest natural resources. To investigate these general methodological and empirical questions, this dissertation undertakes two separate studies.

The first study is described in Chapter 2 and seeks to show how a static spatial analysis of the physical landscape of a natural resource can be used to inform policy making and policy evaluation. It focuses on answering the first methodological question: how to extract information about forest resource change in instances where data on forest condition only exists for one point in time. The chapter argues that in foraging settings, a focus on the geographic dimensions of what a community views as the most important subsistence forest product species, one can reveal new information about human-institutional dynamics and human induced forest change. In the Nepalese case presented, such an analysis is undertaken. Three theoretically-based vegetation patterns are identified and tested based on knowledge of existing physical, community and institutional landscape configurations. The study reveals an important spatial dimension related to the institutional landscape that shifts the human harvesting pressures away from what optimal foraging theory would predict. Findings related to the four empirical questions identified above are reported.

The second study is presented in Chapters 3 through 7 and undertakes an analysis of forest change using a temporal set of Landsat Multispectral Scanner (MSS) scenes in the south-central region of Indiana, U.S.A. This study focuses on methodological questions two through four above, investigating the appropriate use of MSS scenes toward the analysis of human direct action on forests by developing measures of condition using spectral mixture analysis (Adams, *et al.* 1994) and analyzing how these indicators change over time. It addresses the theoretical question of whether we can adequately predict, based on human incentive structures, patterns we see in a time series of remotely sensed images.

These two empirical studies can, in and of themselves, stand on their own. They each investigate their own particular research questions. They each individually incorporate theory relevant to their question, setting and situation and try to build upon that theory. They each provide further detail on the specific analytic methods they employ and strive to answer the four empirical questions listed above. However placed side by side in this volume they cover generally *the two methodological approaches* available if we want to understand *change* in natural resource landscapes. Change in a geographic context can only be detected through either: (1) an analysis of pattern or imprints in a geographic landscape at one point in time or (2) through analysis of change using longitudinal data. I therefore include a final section (Chapter 8) which provides some synthesis and reflection on the lessons learned from each one of these approaches and also consider how each of the two endeavors complement one another and how they might be utilized together. These studies placed side by side also emphasize the informative power that an integration of spatial and temporal analysis and institutional analysis can bring to understanding change in a setting--any setting--be it in a developing or developed world context. Moreover, the studies together provide valuable lessons learned that others involved in the study of natural resource landscapes can apply--landscapes that do not necessarily involve forests.

The analytic approaches I use can just as easily be applied to the study of other natural resource settings (e.g. irrigation, watershed management or even possibly fisheries) or even to the study of change in an urban or suburban landscapes.

Chapter 1 Endnotes

1. Scale refers to the quantitative or analytic dimensions used to measure and study objects or processes (Gibson, Ostrom, and Ahn, 1997) It can refer to geographic space or time and is usually defined by two attributes: resolution and extent. Chapter 5 includes a more detailed discussion of these issues.

2. The United Nations sponsored global climate convention at Kyoto, with over 150 countries represented (Online forum, 1998) provides a good example of how important these issues recently have become.

3. I should note here that much of this chapter refers to "natural resources" generally, including, for example, irrigation and fishery rather than specifically targeting forest resources. I do this because many of the concepts of this chapter and many of the techniques and approaches in this dissertation are directly transferable to the study of other natural resources Part of the power of the methods and analytic approaches presented here are their ability to be utilized in the study of other resources.

4. This framework is a variation of the Institutional Analysis and Development (IAD) framework devised by scholars associated with the Workshop in Political Theory and Policy Analysis, Indiana University. See Ostrom, Gardner and Walker (1994) for a description and history of IAD.

5. In the state of Indiana, for example, a specific fund generated from the sale of license plates with a special 'Indiana environment' emblem, provides the state Department of Natural Resources (DNR) the ability to purchase private land that the DNR deems important to its mission (Fischer, personnel communication).

6. I consider the decision to leave the resource alone at a given location as one particular type of action a actor can choose.

7. It is important to note that there is an intermediate outcome described in Figure 1-1 The "Patterns of Interactions" component of the figure describes changes within the community of actors over a given period of time. For instance, there may be improvements in cooperation between these actors. Similarly, these actors may achieve higher levels of trust between themselves. Further, actors may enjoy higher levels of information regarding the action arena. Or, in each of these cases, the reverse may occur (e.g. lower levels of cooperation, trust or information). The changes in these interactions affect the outcomes that are achieved in each or the three landscapes.

8. In the state of Indiana, for example, two significant studies have been undertaken which have utilized large forest plots covering a broad areal extent. There have been three state wide (actually, the entire east coast from the Mississippi river on) forest inventories conducted: 1950, 1967 and 1986 (see Smith and Golitz, 1988). A fourth statewide inventory is underway. Similarly, a joint venture between Indiana University and Purdue University–the Ecological Classification System study–resulted in the collection of a large number of 500m^2 plots sampled over a wide geographic area.

9. It appears that most spatial analyses in the social sciences appear to involve forests. Very few if any geographically accurate spatial analyses have been conducted on the physical and community landscapes of irrigation systems or other natural resources.

10. I will elaborate on this second point further below. Since patterns over geographic space are a result of spatio-temporal processes, analysis of geographic pattern can reveal new information about the spatio-temporal process that created such a pattern.

11. Until very recently Landsat TM scenes, for example, cost in the range of $4000 a piece.

12. There are a few exceptions that have recently been published. See Stringer *et al.*, 1988; Wolter *et al.*, 1995; Lee and Marsh, 1995; and Sader, 1995

13. While I am not aware of any sensitivity analyses of scale related to human-natural resource relationships, a number of scholars report the presence of scale effects in studies of other phenomena. For instance, Turner *et al.* (1989) describes one study where the sign of the effect of precipitation on oak seedling mortality changed when data was aggregated at local and regional scales. Turner and colleagues also report that similar contradictory findings have occurred in response to changing temporal scales. One study they reference (by Carpenter, 1989) reports that when samples were collected at two to three day intervals a negative relationship was identified between zooplankton and phytoplankton. When samples were collected at 10-14 day intervals a positive relationship was discovered and finally, when the traditional seven day sampling plan was undertaken, no relationship between the plankton was identified.

Figure 1-1: A Framework for Studying the Spatial Dynamics of Natural Resource Systems (Adapted from Ostrom, Gardner and Walker, 1994)

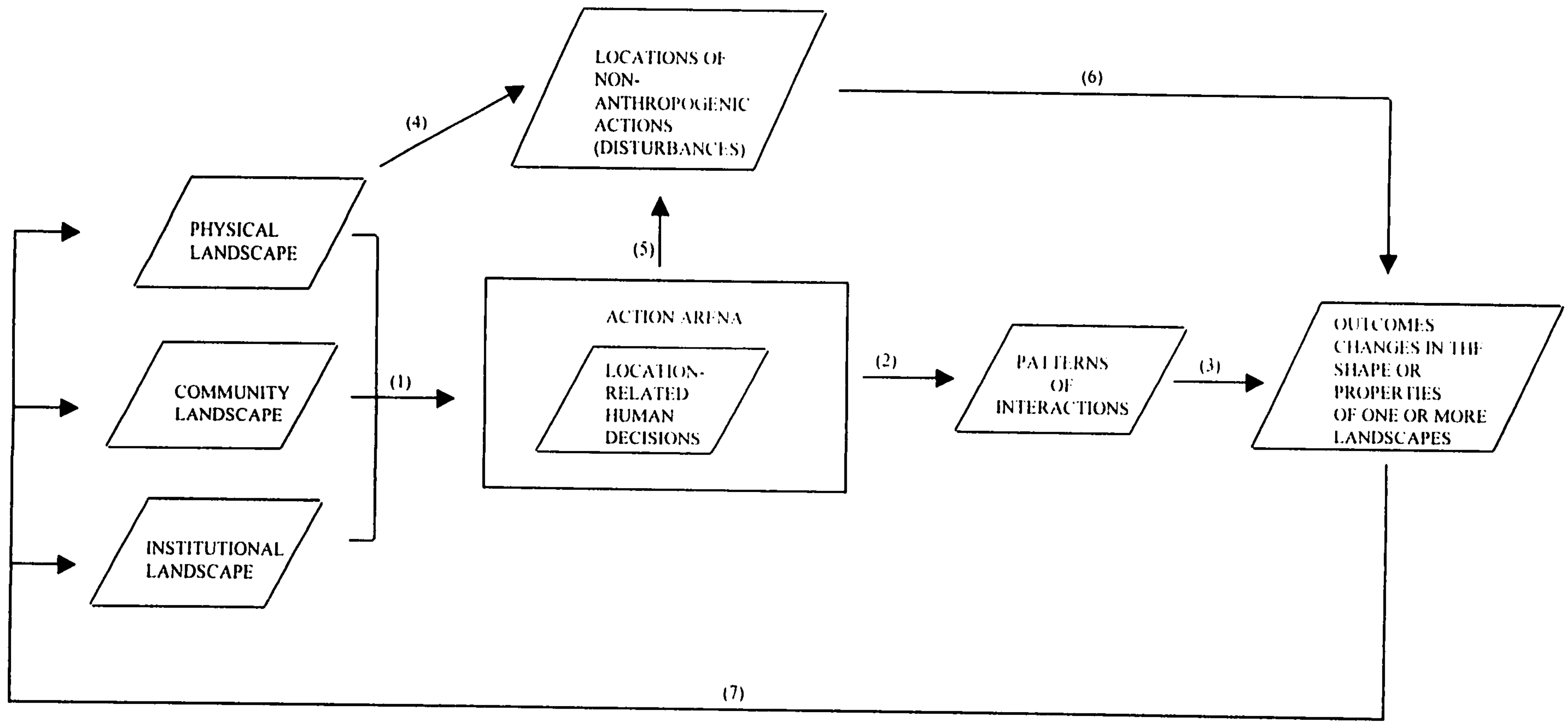
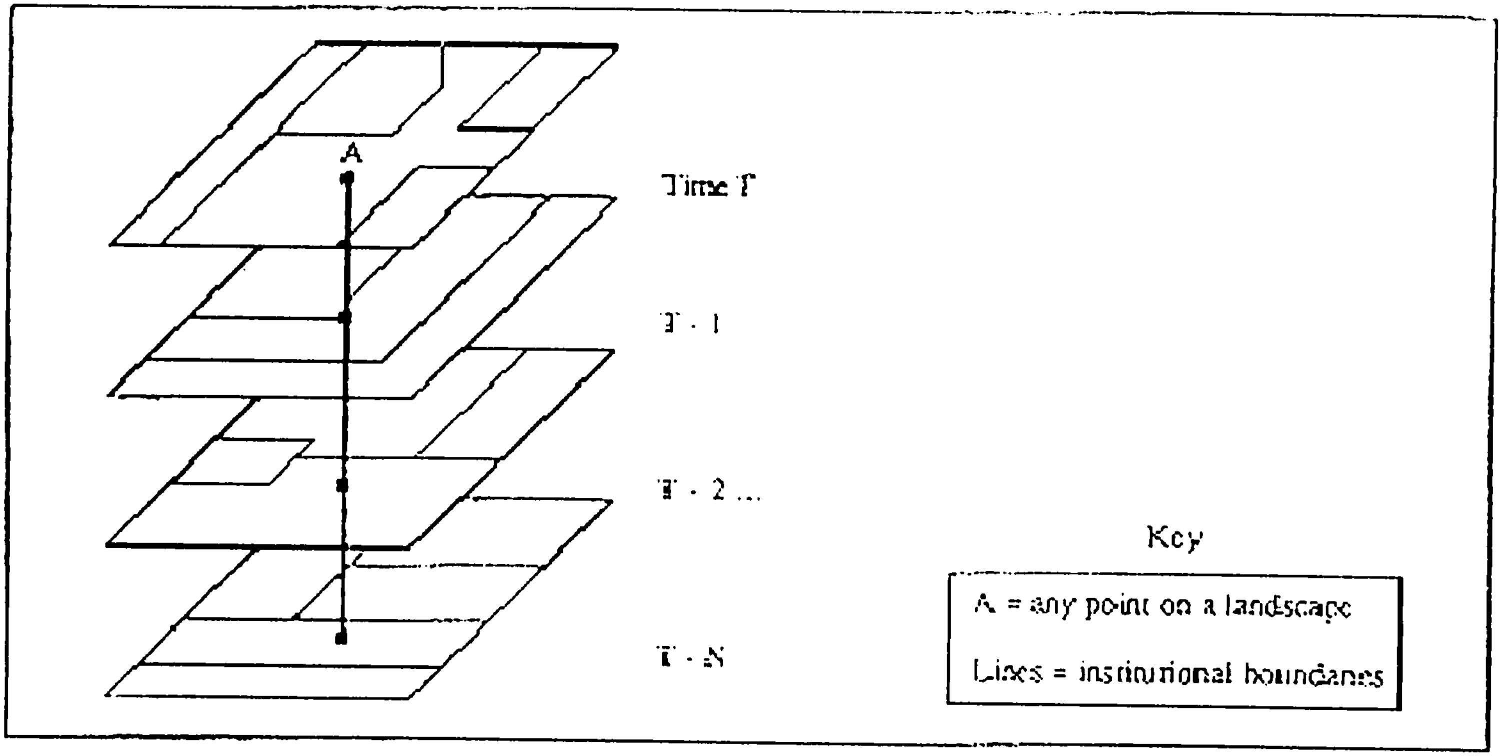


Figure 1-2: Schematic of Institutional Boundaries Changing Over Time



Chapter 2

USING SPATIAL INFORMATION TO UNDERSTAND HUMAN DYNAMICS AND FOREST CHANGE: A STUDY FROM NEPAL

Introduction

Over the past decade, considerable attention has been given to the subject of human induced forest change and the depletion of particular species in forests (Myers, 1988; Aldhous, 1993; Repetto, 1988; Lovejoy, 1980; Task Force on Global Biodiversity, 1989; Norton, 1986; Reid and Miller, 1989). Often, these studies focus on macro political or economic influences (Repetto, 1988; Richards and Tucker, 1988). Other research shifts attention to the individual and searches for deeper understanding of influential variables that influence foraging behavior. Some of these "micro-scale analyses" focus on the influence of institutions that create or modify human incentives and behavior related to forest product consumption (Ascher, 1995; Angelsen, 1995; McKean, 1992; Thomson, Feeny, and Oakerson, 1992; Ostrom and Wertime, 1995; Morrow and Hull, 1996).

Micro-level investigations concerned with understanding the human impacts on forest change require some capacity to quantify forest condition and some method to analyze change in that condition. The standard method of quantifying forest condition is to (1) take a sample of vegetation using forest plot measurements, (2) calculate species abundance indicators (e.g., species density, dominance or frequency) from these plots, and (3) use these indicators to describe the current status of the forested area as a whole. Plot-level analyses are also sometimes conducted (see for example, Umans, 1993), but usually without attention to the spatial distribution of the plots. If the researcher is ***extremely*** fortunate, prior data may have been collected on forest condition and these baseline data can be compared with newly collected measurements. General conclusions can then be made regarding the change in forest resources and the impact of current institutional arrangements and forest policies on human foraging incentives in the region.

Unfortunately, as argued in Chapter 1, it is rare to find a study location that actually has had a prior forest inventory conducted. In most cases, especially in developing world settings, we have information gaps: no prior data exists on the condition of a forest we set out to study. Understanding change in the resource in this context is quite difficult, for no baseline data exists for comparison. Even in the rare circumstance where a baseline dataset exists, it is either not georeferenced, or is georeferenced in an aggregated form. In such cases, we run into the "ecological inference" problem (King, 1997): we may know that change has occurred, but we may not know where the "hots spots" of change (e.g., deforestation fronts) are located.

So, how then do scholars and policy-makers who are interested in understanding the human dimensions of forest change overcome this problem? Scholars from geography, anthropology, and other disciplines have long been aware of the informative nature of spatial relationships: yesterday's human actions often leave imprints that remain apparent in the landscape of the natural resource of today (Pickett and Candenasso, 1995; Keller, et. al., 1996). In circumstances where we lack longitudinal data we can still extract new information related to change through the study of these patterns. Unfortunately, up until very recently, our ability to capture spatial relationships was hampered by our inability to collect accurate spatial data. However, the emergence of differential global positioning system (DGPS) technology provides new opportunities for the accurate georeferencing of data. Armed with this new information and the digital processing capabilities supplied by geographic information systems (GIS) and spatial statistics, we can more easily collect accurate georeferenced data and analyze it for expected spatial patterns. Spatial analysis provides an opportunity to extract additional information about forest change in instances where no baseline forest condition data exist (Schweik, 1997).

Further, in addition to overcoming the "no baseline data" problem, spatial analysis at a forest plot level may help shed light into community dynamics—something that might be missed using data aggregated at the forest level. For example, in agrarian societies that depend on forest products for subsistence, the existing spatial distribution of an important forest product species may reflect human foraging decision making in response to the physical geography and established harvesting rules or social norms. Over geographic space, particular forest locations may be subject to heavier harvesting as foragers respond to constraints and opportunities posed by existing community relationships and forest-governing institutional structures. To the researcher or policy-maker interested in understanding how community inequities and governance arrangements influence the harvesting behavior of foragers, a spatial analysis could be quite revealing.

Objectives of this "Spatial Analysis" Study

There are two primary objectives of the study undertaken in this chapter. The first objective is to address the initial methodological question presented in the first chapter:

> *M1) How do we apply a spatial analysis to extract additional information about change from a one point in time geographically referenced dataset?*

This chapter answers this question by developing a new methodology—by combining recent advances in DGPS, GIS, institutional analysis and maximum likelihood regression—to tease out the human dimensions of forest change using a cross sectional forest plot dataset.

The second objective is to address the four empirical questions presented in the introductory chapter in this Nepal forest resource context.

> *E1) Where has change occurred in the physical landscape of the forest resource and where has it remained stable? And how are these linked to policy issues?*
>
> *E2) What direct human actions have taken place over time that have contributed to the change we witness in the physical landscape of the forest resource?*
>
> *E3) What are the indirect forces—the configurations of community and institutional landscape attributes—that have led humans to undertake these activities?*
>
> *E4) What temporal patterns in the community and institutional landscapes appear to have led to resource conditions we might consider as "positive" or "negative"?*

The chapter is organized in the following manner. First, the study site and data collection methods are described. Second, more detail is provided on the setting, focusing in on the forest governance arrangements and human foraging patterns based on villager accounts and what we observed in the field. Based on this knowledge of the foraging setting and institutional configurations, plausible geographic patterns in the distribution of a particularly important forest species are presented. Third, a brief, more traditional analysis of aggregate forest condition data is presented. Several issues are raised in regard to understanding forest change using these aggregated measures. The fourth section then turns to a more detailed spatial analysis of the data. The theoretical foundations and a "species density" forest plot model are established. This model contains a spatial component to capture the expected patterns in the data that are a result of past human foraging practices. The fifth section provides an overview of the statistical methods applied. Specifically, techniques used for identifying the natural, undisturbed spatial distribution of the species of interest and results from the statistical model are presented. Finally, a discussion of the results is presented and the paper concludes with reflections on some of the techniques used.

The Study Site and Data Collection

In October 1994, forested areas within the Kayar Khola watershed in the Chitwan district of southern Nepal were chosen for study (Figure 2-1). The Siwalik hills of Nepal, especially in the district of Chitwan, are under a tremendous amount of human pressure (see for example, Shrestha, Velu and Conway, 1993) and therefore were considered an appropriate location for research. The project, a part of the larger International Forestry Resources and Institutions (IFRI) research program, gathered information regarding forest governance, use, and conditions along with socioeconomic attributes of villages that utilize these resources (Ostrom and Wertime, 1995). A research team comprised of Nepali researchers[1] and the author spent six weeks living in the field learning from the villagers about their foraging practices and the institutions governing forest harvesting and management. The research area is located at the juncture of the Kayar and the Shaki river systems. Figure 2-2 presents a scanned and geometrically rectified 1995 topographic map of the region. This map was created by His Majesty's Government of Nepal (HMGN) through interpretation of 1992 aerial photographs of the region. Grey areas designate forests and white areas reflect either degraded forest or areas under some agricultural regime.

Figure 2-1 about here

Three general communities exist in the study area: Milan on the west bank of where the Shakti and Kayar rivers converge, Shaktikhor to the east along the banks of the Kayar, and Latauli to the north of Shaktikhor, up into the hills.[2] A fourth community, Chherwan, higher in the hills was not part of the IFRI study but discussions were held with villagers from there were made later during a subsequent field study.

Figure 2-2 about here

In general, the villagers in the western village of Milan are relatively more well off than the other communities—many households own good land along the river with ample access to water to irrigate rice fields. Milan also exhibits more heterogeneous population when compared with the other two eastern communities, with most members from the Chepang, Chettri and Newar ethnic groups but others such as Brahmin, Tamang, Gurung and Magar are also represented. The eastern villages of Latauli, Shaktikhor and Chherwan also are comprised of subsistence farmers living in areas where it is more difficult to irrigate given their topographic setting. Consequently they settle more often for other crops such as maize that require less water, are hardy and less commercially valuable.

The scanned topographic map provided by HMGN in Figure 2-2 is also helpful for it identifies household point locations within these villages. These point locations were also interpreted from the 1992 aerial photos and reflect fairly accurately what we observed in the field. In a few instances (especially in eastern hilly regions), additional household locations were digitized where they were not sufficiently represented on the HMG map so that the GIS most accurately reflects villager household estimates and configurations identified during the IFRI study. These estimates are presented in Table 2-1.

Table 2-1 about here

Forests, Forest Governance, Use and Possible Outcomes

The majority of the villagers in each of these three communities are subsistence farmers and depend heavily on forest products for their livelihood. The term "forest," as defined by the IFRI research program, is an area encompassed by some woody biomass, larger than .5 hectares in size, governed by a similar governance structure, and utilized by at least three households.

Three forests, by this definition, exist at the study site: to the west, Sugabhanjyang forest; to the east, Latauli forest; and to the south, Kaswang forest (Figure 2-2). They all are semi-deciduous, climax *Shorea robusta* forests.

All three forests in the study area are designated official "government forests" and fall under the management of the District Forest Office (DFO). The DFO manages forests though Village Development Committee (VDC) boundaries which are the smallest political units in the Nepalese administration system. A VDC boundary runs directly up the Kayar river in the south west and then follows the Shakti river northward effectively placing the western Sugabhanjyang forest under a different VDC jurisdiction from that governing Kaswang and Latauli.

There are three formally established DFO rules related to forest product use. First, anyone who is a member of a VDC is permitted to harvest grass, tree fodder, and deadwood from forests within that VDC to fulfill their daily subsistence requirements. Second, live trees can only be felled if formal written permission is received from the DFO prior to harvesting. Third, a "no encroachment" rule exists that prohibits the conversion of DFO forest land to some other land use.

DFO guards stationed at VDC range posts are responsible for the enforcement of these rules. These DFO range post offices are a significant distance away from the forests: the range post responsible for the monitoring of Sugabhanjyang is located approximately 14 kilometers to the southwest of Milan, and the DFO range post for Latauli and Kaswang is located approximately 16 kilometers southeast of the village of Latauli (both well off the map in Figure 2-2). At each range post, approximately 10 guards are stationed. These guards are responsible for patrolling--largely on foot--a hilly, almost mountainous area that extends over 100 square kilometers. Their task is daunting and their effectiveness appears to be quite limited. It is not surprising that their efforts, while weak everywhere, appear to be a bit more effective in geographic locations more easily accessible from their range post locations. Villagers report relatively few interactions with forest guards. When they do occur, however, they tend to be more frequent in areas along the motorable road through Milan on the southwest side of Figure 2-2. At one point during our field work, the research team witnessed the enforcement of the no-encroachment rule. DFO guards destroyed the home of a person who encroached upon land in the southwestern tip of the Sugabhanjyang forest. The guards then hauled the building material away on a truck. This incident, while reportedly rare, proves that there is limited rule enforcement by the DFO in areas reasonably close to the motorable road through Milan.

The map in Figure 2-2 shows the road crossing the Shakti river and going through the eastern village of Shaktikhor. This map is misleading, for crossing this river in a vehicle at any time of the year is quite difficult. The convergence of the two rivers at this junction leads to a process called "the backwater effect" (Bruijnzeel and Bremmer, 1989: 64) where tremendous quantities of boulders and rocks are deposited in the Shakti river bed. Motorable crossing here is very difficult even in the dry season. The result, confirmed by villager reports, is that the monitoring of the Latauli and Kaswang forests by DFO guards is much less frequent than is found in Sugabhanjyang.

While the formal DFO rules appear to be well understood, in many respects they are not followed: what we observed in the field proved that these rules were always being broken. Forest use by all villagers in all communities appears to be very much the same. Villagers harvest timber for construction and for tools; fodder, leaf litter and grasses for livestock and other agriculture purposes; and fuelwood for cooking and heating purposes. We witnessed these types of foraging activities during our weeks in the field. People from all villages reported that two major human activities are causing what they deem as a rapid depletion of their forest resources. The first, is forest conversion to agriculture. The second is forest product extraction: the harvesting of timber, fuelwood, and tree fodder (lopping). Tree lopping is especially prevalent, which, as Metz (1990: 285) notes, significantly reduces the opportunity for species to regenerate.

The slash and burning of forest land for agriculture perhaps is the most extreme DFO rule violation and this practice is prevalent especially in higher locations in the hills. This aspect of the human-forest dynamics is described in more detail in Schweik, Adhikari and Pandit (1997) However, foraging-related violations also occur frequently. The families from the western village of Milan, more wealthier (relatively) and ethnically diverse, report that they harvest not only from the Sugabhanjyang forest in their VDC, but they also lop trees for fodder and gather grasses from the Latauli forest in the neighboring VDC This forest is over one kilometer away to the east and uphill (see map in Figure 2-2). This is a direct violation of the DFO established rules in the area. Interestingly, the villagers from the eastern communities of Shaktikor and Latauli don't seem to mind. No complaints have been registered to the DFO range post. Even more puzzling, the villagers from the eastern communities of Shaktikhor, and Latauli, on the other hand, report that they forage in the Latauli forest only. They explain that most of the year the Kayar river flows too wide for them to access the Kaswang forest to the south, and that no consideration is even given to harvesting in the Sugabhanjyang forest in the neighboring VDC. Research team members who lived in the villages, held numerous discussions with villagers about foraging behavior, and monitored forest harvesting activities for nearly six weeks, confirm this behavior (Shrestha, 1996). Each side adapts a "that's just the way it is" type of attitude when asked about these foraging patterns. It appears, then, that an unwritten social norm exists across communities that effectively permits western (Milan) villager foraging in the eastern Latauli forest but doesn't allow the converse to occur. Some of this may be due to ethnic hierarchies, and some of it may be because some villagers in Shaktikhor work for people in Milan in their agriculture fields. This community dynamic adds additional foraging pressure—particularly lopping pressure—on the Latauli forest, a forest already heavily used by the Shaktikhor, Latauli and Chherwan villagers.

Anticipated Patterns in Forest Vegetation

From the previous discussion, we are now in a position to develop hypotheses related to forest vegetation patterns given what we know about the forest governance structure and monitoring capacity, forest product uses, geographic locations of households, and community relationships. In this setting, one of three patterns of vegetation over the landscape are likely.

Pattern 1: No Human Influence

The first possible pattern is one of a "naturally" distributed forest ecosystem where human activity is so minimal that the forests are able to replenish at a rate faster or equal to what is being removed. The pattern of vegetation in any forest, then, would be no different than what would be found in a comparable forest in a similar ecological setting that has not been influenced by human harvesting. Each particular species follows its own "naturally induced" distribution over the topography. The graphic in Figure 2-3a describes this landscape. The likelihood that this type of pattern exists in Sugabhanjyang or Latauli is doubtful, however, given that villagers from all communities report that these two forests have been significantly degraded over the past 20 years.

Figure 2-3a about here

Pattern 2: Open Access and Optimal Foraging

The second pattern that might be identified in forest vegetation is one that reflects an "institutionally-free" open access situation where human decision-making and harvesting is driven simply by optimal foraging strategies. Optimal foraging theory depicts human foragers as actors who maximize their net rate of return of energy per unit of foraging time (Smith, 1983). While a number of alternative theories on foraging decision making exist (see Smith, 1983: 627), they all characterize the forager as a person who strives to minimize his or her search time and effort (Hayden, 1981; Winterhalder, 1993). If humans harvest a particular species at a rate higher than can be regenerated by the forest, optimal foraging would predict that fewer important product species will be found in locations easily accessed by humans (e.g., a short distance away from the village, near a path, or at a lower elevation).

In the context of this site, we would expect important product species to be higher in number in areas further away from villages and at higher altitudes where it is more difficult to walk. Alternatively, the density of important product species would be lower in areas that are approximate to household locations. Consequently, we would expect Kaswang to exhibit a high degree of "naturally induced" species distribution, given that it is well protected from foraging by the river systems and few human settlements exist within or near it. We'd also expect the northern part of Sugabhanjyang to exhibit a relatively "natural" condition, given that it is high up in the hills and no villages exist to the north. Alternatively, we'd expect the southern half of the Sugabhanjyang forest near Milan to be relatively hard-hit in terms of foraging pressure, as well as on the eastern side of Latauli where the forest is completely surrounded by settlements. Finally, given population locations, optimal foraging would predict that the forest most affected would be the western side of Latauli--the part in the center of the map that sits in between Milan, Shaktikhor and the upland village of Latauli. 2-3b depicts this optimal foraging induced landscape

Figure 2-3b about here

Pattern 3 Optimal Foraging Combined with Institutional Influences

Smith (1983) reports that empirical studies testing optimal foraging theory have revealed that in some instances human foragers are selective in their utilization of available resources. Other studies have revealed foragers who exhibit much less concern. Smith also states that there is little agreement in the anthropological community over these foraging differences (1983: 628-29). While not stated specifically, Smith's discussion alludes to the importance of community relationships and the important role institutional arrangements play in altering human foraging patterns and in the preservation of natural resources.[3]

Ostrom (1990) extends Smith's argument by emphasizing the role institutional arrangements play in altering the incentives humans face in their decision-making context. Institutions in this context refer to the property rights and rules-in-use that govern the harvesting of a particular species or of particular areas (what we might refer to as management units) within a forest. The institutional composition in this setting is such that the forests are, to a significant degree, open access. The expectation is that optimal foraging patterns will prevail. But, the possibility exists that foraging decision-making over the years may have been altered by what I have referred to as the past and present "institutional landscape" configurations (Schweik, 1997). The institutional landscapes in this setting, albeit weak (see Schweik, Adhikari and Pandit, 1997, for more detail), still may have altered human foraging behavior to some limited degree. If this is the case, the vegetation pattern across the landscape would reflect a new optimal foraging cost-benefit calculus, where the decision to harvest or not to harvest at a particular location includes a consideration of rules, rule penalties and the likelihood of getting caught breaking a rule (Ostrom, 1990, 1997).

In the site description presented earlier, there exist two primary institutions that appear to be somewhat influential in driving human decision-making away from what optimal foraging might predict: the monitoring practices along the road in Milan and the established social norms that exist between the Milan and Shaktikhor communities. In this case, DFO monitoring appears to be relatively ineffective, with the exception of forested areas adjacent to the road through Milan. This more active forest monitoring by DFO guards in the west could supply an incentive for the Milan villagers to harvest in the higher regions of Sugabhanjyang and across the river into Latauli *in locations that are not visible from the road*. This, in conjunction with the interesting social dynamic we observeded—the unwritten or accepted rule which allows villagers of Milan to harvest in the Latauli forest but not vice versa—places added pressure on the eastern side of the Latauli forest. Thus, in a setting where both optimal foraging and these institutionally induced incentives are present, one would expect a landscape that reflects more of a continuous loss of species individuals in the forest—a species depletion trend—as one moves from the west to east (Figure 2-3c).

Figure 2-3c about here

Traditional Methods of Forest Condition Analysis and Their Limitations in Ascertaining Forest Change

With the situation described, let us first undertake the more traditional "aggregated" analysis of forest condition to see if there is evidence to support either of the three possible patterns.

Forest Plot Data Collection

Our IFRI study utilized a traditional forest plot sampling to measure condition for each of the three forests identified. The team included one forester, one botanist and several assistants, and utilized ten-meter radius circular forest plots for sampling. Due to the steep terrain within these forests, the team followed trails to reach fifty-meter altitudinal intervals. At each location, a random number was used to determine the direction and the distance from the trail that the corresponding plot should be taken. Overall, 97 forest plots were sampled (Figure 2-2). Data recorded include:

- soil characteristics, such as the depth of the humus layer, and the depth and color of the "a" and "b" horizons;
- tree identification, including diameter at breast height, height and species type for each tree within the plot;
- sapling and shrub information;
- plot physiographic information, such as slope (in degrees), elevation (using an altimeter) and aspect (the direction the slope faces);
- ancillary observations, such as the existence of insect damage, signs of animal grazing, and evidence of human harvesting.

We also did something rather unusual--but soon to become more prevalent. We were fortunate to have two eight-channel GPS receivers and a laptop computer with us in the field. This allowed us to collect accurate positional data regarding these forest plots. It is generally agreed that a single GPS unit working alone in the field is capable of providing location coordinates (e.g., longitude/latitude or UTM projection) accurate to approximately 100 meters (Pace *et al*, 1995; August *et al.* 1994). For any analysis conducted at a forest-plot level, 100 meter error (radius) is too great. Plot positions would be erroneous using a one-GPS receiver technique. However, using two receivers together--a technique which employs one GPS machine with a laptop computer as a "basestation" at a known location, and the other GPS collecting data in the field--can improve positional accuracy to about 1-5 meters (Pace, *et al*, 1995). The process, referred to as "post-processing differential correction," is explained in detail by Pace *et al.* (1995) and on a variety of GPS related internet sites. Using differential GPS techniques, we were able to collect accurate forest plot positions in longitude, latitude and UTM coordinate systems. These positions were then converted to a GIS point coverage and are overlaid on the georeferenced map presented in Figure 2-2

A Focus on Important Product Species

If we are interested in understanding deforestation practices in a foraging community, it is most helpful to focus analysis on the species the communities find important. My point here is simple: in any setting where foraging levels are high, the severity of the deforestation will manifest itself *first* in the distribution (or lack thereof) of the species that contributes the most to villagers' daily subsistence requirements. The villagers in all communities mentioned the same five tree species as the ones most useful in supplying their timber, fodder and fuel wood needs. The most important one is *Shorea robusta* (referred to as "Sal" locally). Four other species were also mentioned as highly valuable: *Nycthanthes arbortristis* (Parijat), *Adina cordifolia* (Karma), *Lagerstroemia parviflora* (Botdhainyero), and *Terminalia tomentosa* (Saj).

An Aggregate Forest Plot Analysis

A comparison of the mean diameter at breast height (DBH) and the mean height of each of these species for each forest are presented in Figures 2-4 and 2-5. While there is some fluctuation in mean DBH between forests for particular species, nothing strikingly different is identified in this comparison.

Figures 2-4 and 2-5 about here

Figures 2-6, 2-7, 2-8 and 2-9 provide a comparison of absolute density, frequency and dominance and species importance values of these species across the three forests. Density (Figure 2-6) is determined by counting the number of individual trees in each species and then dividing this by the total area sampled. Frequency (Figure 2-7) provides a measure of how widely a species is distributed within a forested area. It is calculated by taking the number of plots in which a species occurs and dividing this by the number of plots sampled. Dominance (Figure 2-8) provides an estimate of the standing biomass a particular species contributes to a forest composition. Dominance is calculated by taking the total basal area of a species and dividing it by the area sampled. Finally, the importance values (Figure 2-9) of each species reports the sum of the *relative* density, dominance and frequency together divided by three. These aggregate measures are commonly used when comparing the conditions of different forested areas.

Figures 2-6, 2-7, 2-8 and 2-9 about here

These figures provide strikingly hard evidence to support villager concerns of forest species depletion in the Sugabhanjyang and Latauli forests. The Kaswang forest—the relatively untouched forest—is quite different from the other two. In the density, dominance, frequency and importance value charts, Kaswang reflects a very different composition with a much higher presence of the important product tree species *Shorea robusta*—something we would expect in a *Shorea robusta* climax forest.

But beyond the striking evidence produced from a comparison of Kaswang to Latauli and to Sugabhanjyang, it becomes less clear from this cross-sectional aggregate data how the forest landscape has been transformed by human activity. It is clear that Sugabhanjyang and Latauli are comprised of differing levels of vegetation than is Kaswang, but we cannot easily identify whether Latauli or Sugabhanjyang follow patterns of optimal foraging in Figure 2-3b or optimal foraging coupled with institutional influences in Figure 2-3c. In fact, the lower measures found in Latauli and Sugabhanjyang could also be a result of purely natural forces: the topography or soil conditions could be less hospitable to these species in Latauli than in Sugabhanjyang. It could be that Latauli *always* exhibited fewer *Shorea robusta* individuals than its neighboring forests. We simply can't make any strong statements about forest change from these aggregated data alone.

Using Geographic Relationships to Understand Change: A Spatially Explicit "Species Density" Model

The argument made earlier is that by giving some extra consideration to spatial relationships and testing for these factors we can improve our understanding of forest change in instances when baseline forest condition data is unavailable The intention of the rest of this paper is to develop a spatially explicit model that captures the influence of the foraging dynamics as reported by villagers. Multivariate regression will be used to test this model But before proceeding to the statistical methods and results, a brief theoretical discussion of important variables for the model is provided, along with the methods used to operationalize these variables. Figure 2-10 summarizes the model as outlined in this section.

Figure 2-10 about here

The Dependent Variable: A Measure of Species Density or Abundance

A spatial analysis requires forest plots to be the unit of analysis rather than aggregate forest measures. I have argued earlier that it is helpful to focus on one important forest product species in this analysis. If we are concerned about the overharvesting of this species, we should work to explain the presence or absence of this species in a forest plot. Given that *Shorea robusta* is deemed so valuable and important to the villagers in these communities, a count of the number of these trees in a plot provides a simple but useful measure of species abundance.

The Independent Variables: Factors that Influence Where *Shorea robusta* Exists

Many factors determine whether a species is found in a particular plot. These influential factors can be divided into abiotic stresses, biotic stresses, and human stresses.[4]

Abiotic stresses

Each forest plot has physiographic characteristics that influence the capacity for a particular species to grow in its environment. These characteristics include slope, aspect (or slope orientation), elevation, and soil type and condition. These attributes can play a tremendous role in the number and type of species that exist within a plot. Variation in the topography and soil provide specialized environments that encourage or discourage particular species to grow (Spurr and Barnes, 1992). Slope steepness and aspect are two crucial factors that determine whether a particular species will survive within a given forest plot. These variables dramatically influence the micro-ecosystem characteristics—exposure to sunlight, rainfall, and so on—that exist within the plot. Any model that attempts to explain human impacts on a forest environment must control for these features. The field team recorded slope steepness in degrees with a clinometer.

A review of the topographic map provided in Figure 2-2 reveals the hilly nature of this environment. We would expect then, that the steeper a slope is, the more difficult it would be for a *Shorea robusta* tree to establish sound root systems. Slope aspect captures the direction a slope faces. In the field, the general aspect of the plot was noted. Aspect is operationalized here as a categorical variable: a zero represents a north-facing slope; a one represents either a northwest or northeast facing slope; a two represents an east or west facing slope; a three represents a southwest or southeast facing slope and a four represents a completely south facing slope It is not clear what effect, if any, aspect will have in this area. Given that the Nepal Terai is located in a subtropical region, all slope types may receive generally comparable levels of sunlight over a one-day period. I include aspect in the model to capture any influences it may have.

Soil nutrients, moisture, and physical composition are also highly influential factors in the growth and survival of particular species. Three soil horizon depths are typically reported in soil analysis: the "O" horizon (humus or ground litter layer), the "A" horizon (a darker mineral layer at the top of the soil), and the "B" horizon (the soil deeper in the ground). The color of these layers as well as textures (sandy, loamy or clayey) are also important determinants in what species can grow in the area. A soil analysis was performed on each forest plot which includes depth, color, and texture of these horizons (IFRI, 1994). These soil measurements are included in the model to capture any influence they may have on the presence of *Shorea robusta* trees.

Other natural disturbances also influence what grows in a particular area. A plot area may be subject to severe weather damage caused by a lightning strike or a fallen tree. This damage results in renewed competition by the vegetation that survived. The IFRI forms record observations for each plot on natural disturbances, but there were no major evidence of weather related disturbances identified in or around forest plot locations.

Biotic Stresses

The number of a particular species within a plot is also influenced by a variety of biotic environmental stresses. The existence of competitor tree species in a forest plot are highly influential in determining whether another species can survive in that particular location. Competition for light, moisture, and nutrients exists in every plot, and species that can better tolerate the plot's conditions with respect to other species will have a better opportunity to grow. Since all trees in each plot were identified, measured, and entered into the IFRI database, this analysis uses a measure of competing tree biomass--a summation of the diameter at breast height (DBH) for species other than *Shorea robusta*--to capture the influence of rival species within each plot. We would expect that the more competitor species there are in a plot, the less likely *Shorea robusta* species will be found.

The proximity of neighboring *Shorea robusta* seed trees often determine if a tree will grow in a particular plot. The type of seed and its transportation medium influence where it may grow. The seed of a *Shorea robusta* is a samara[5] and may be carried a great distance by wind disturbances (Storrs and Storrs, 1990). Given that these seeds can potentially travel great distances, and that these forests are all *Shorea robusta* climax forests stocked even now with *Shorea robusta* species (see Figures 2-4 through 2-9), it is safe to assume that each forest plot has an equal likelihood of having *Shorea robusta* seed trees somewhere in its vicinity.

Animal grazing activity also influences species survival within a plot. Animals forage for particularly tasty or nutritious species and these grazing habits often then determine the fate of many seedlings. In contrast, species not particularly interesting to animals may continue to survive or even thrive. However, the grazing of livestock is closely related to the location of households and therefore that influence will be captured through a variable related to human activities discussed below.

Human Stresses--foraging pressures

Now we turn to the problem of how to best operationalize human foraging pressures for this model. Given our understanding of the geographic, topographic and institutional composition of the setting, we can attempt to establish some "plot accessibility" measure that would capture the influence both of optimal foraging and of institutional influences on human harvest decision-making. Ideally, some measure of effort or cost could be quantified for each plot that accounts for both optimal foraging decision-making and also the effects of institutional arrangements and monitoring/sanctioning mechanisms. Four methods were considered, and two were actually applied.

The first method considered to capture optimal foraging was to calculate the distance from each plot to the center of a village or villages. This is a simple measure to calculate using a GIS, but it is difficult in this circumstance to identify just what exactly is "the village." A glance at the household configurations for the villages in Figure 2-2 proves this point. Households in each community are scattered throughout the landscape. There is no easy (or useful) method of determining a distance to plot from a village centroid. This approach was rejected.

The second method would be to somehow measure the distance of each plot from trails within the forest. Once again, with trails digitized in a GIS system this is a fairly straightforward task. However, two reasons make this approach impractical. First, the trails on the current map do not accurately reflect what we know to exist in the field. The map in Figure 2-2 shows only a few trails, yet, we know that in Sugabhanjyang and Latauli, there are elaborate series of trails criss-crossing throughout each forest. We could attempt to digitize trail locations based on our knowledge and hand drawn maps of the area, but the error in placing these trails would be high enough that using distance to plot as a measure would lead to possibly erroneous results. For this reason this approach was also rejected.

The third method considered to quantify optimal foraging pressure was to develop (1) a count of the number of households within a certain distance from each plot and (2) a measure of the distance all these households are from the plot. This approach was used. Figure 2-11 provides an example of how this measure was calculated for three forest plots. Using the GIS household coverage, the Arc-Info™ GIS "pointdistance" function could be utilized to calculate the distances between one GIS point layer (forest plots) and another point layer (households) within a 1-kilometer search radius. While in some instances foragers may go beyond one kilometer to forage, this distance assumption is reasonable given what villagers have told us and given the hilly terrain these people actively forage. From the output provided by the pointdistance function, distance measures for all households within this radius to each plot and household counts could be easily quantified. We would expect that plots would have less *Shorea robusta* trees if there are a larger number of households within a kilometer. We would also expect that the closer these households are to the plot the less trees these plots would have on them. One limitation of this method of quantifying foraging pressures is that it does not take into account the institutional attributes governing the areas within which the forest plots fall.

Figure 2-11 about here

The fourth method considered in the development of a plot accessibility measure tries to account for both the optimal foraging dynamics and the institutional setting of the area. This took some hard thinking about the dynamics of the foraging setting using Figure

2-2, and tries to capture the pattern described earlier in Figure 2-3c. Given that the Sugabhanjyang and the Latauli forests lie generally in a west-east relationship, the possibility exists that the optimal foraging patterns coupled with the existing institutional configurations produce a forested landscape that is more depleted as one moves from west to east. In the past, geographers have applied coordinate systems as independent variables--what is commonly referred to as trend surface models--to capture the influence of trend across a landscape. For this reason, the use of DGPS produced X and Y coordinates were added to the model to capture these institutionally induced foraging dynamics.

Statistical Methods and Results

In this section, multiple regression estimation is applied to the model shown in Figure 2-10. Traditional Ordinary Least Squares (OLS) regression assumes the underlying distribution of the dependent variable to be a normal, bell-shaped curve. The dependent variable—the number of *Shorea robusta* species in a plot—is an event-count variable.[6] Long (1997) notes that count variables are often treated as continuous and the linear regression model is applied. This leads to estimates that are inefficient, inconsistent and biased. Further, Ludwig and Reynolds (1988) state that a normal distribution assumption is often not correct when counts of biological phenomena are utilized. King (1989) argues that maximum likelihood estimation (MLE) is a better approach, for it allows the researcher to specify both the distribution of the dependent variable and the relationship that independent variables have with the dependent variable (referred to as the "functional form" of the model).[7]

MLE Assumption 1: Identification of the natural distribution of the *Shorea robusta* species using a reference forest

The first assumption required for MLE is the identification of the most theoretically appropriate distribution of the dependent variable This distributional flexibility of MLE avoids residual violation problems that traditional OLS estimation encounters. MLE requires the identification of the distribution of this event-count variable, and our investigation requires that the distribution be in a setting that is relatively undisturbed by human activities.

Counts of biological species usually follow one of three types of spatial arrangements: random, clustered, or uniform (Ludwig and Reynolds, 1988). In the case of a random dispersal of species, each plot has an equal chance of hosting a *Shorea robusta* individual, resulting in a frequency distribution that is normally distributed (centered around the mean). In such random patterns, the variance will be very close to the mean in value. The second pattern, a clustered pattern, is commonly found in biological studies and follows a negative binomial distribution. Clustering will result in a large number of plots where no *Shorea robusta* individuals are identified. The variance in a clustering pattern will be greater than the mean. Finally, the third pattern often identified is a uniform pattern where almost every plot exhibits the same number of *Shorea robusta* individuals. In these spatial patterns, the variance will be less than the mean (Ludwig and Reynolds, 1988).

A "reference forest" is required to identify the natural distribution of the *Shorea robusta* species.[8] A reference forest is a forest that provides an adequate representation of what the other forests whould be like if undisturbed by human activity. Given what we know about the Kaswang forest, this condition is satisfied. First, it is an adequate representation of the other two forests for because the Nepali foresters in the field identified all three as *Shorea robusta* climax forests. While each forest exhibits generally different slope aspects, given that this region of the earth is subtropical, it is safe to assume that each forest receives comparable amounts of sunlight exposure during the day. Second, given Kaswang's natural protection from human harvesting due to the river systems, it appears to be the forest that exhibits the least exposure to human foraging. The aggregate measures in Figures 2-4 through 2-9 confirm this. For these reasons, I utilize the 31 forest plots sampled in the Kaswang Forest *separately* as the reference forest to determine a natural distribution of *Shorea robusta*. The multiple regression model then utilizes the forest plot data from the Sugabhanjyang and Latauli forests only.

The variance-to-mean ratio or index of dispersion test (Ludwig and Reynolds, 1988) identifies the natural distribution of the *Shorea robusta* count for the Kaswang Forest (Table 2-2). The value for the Chi-squared statistic (df 30) is larger than the critical value at the .01 probability level, implying that *Shorea robusta* in natural settings follows a clumped pattern (variance is greater than the mean).[9] This suggests that the dependent variable, the number of *Shorea robusta* species per plot, follows a negative binomial distribution in an undisturbed setting (Ludwig and Reynolds, 1988: 24). Therefore, a negative binomial is the appropriate distributional assumption for maximum likelihood estimation for this analysis.

MLE Assumption 2: Identifying the Model's Correct Functional Form

The second assumption MLE requires is the specification of the model's functional form. This requires the researcher to specify relationships (e.g., linear or nonlinear) between the dependent variable and each independent variable. An assumption of strict linearity is reasonable for specifying the relationships in Figure 2-10. There is no theoretical justification for the inclusion of exponential components. With the two assumptions for MLE regression specified, a negative binomial maximum likelihood was estimated.

Statistical Results

The results of the maximum likelihood estimation are presented in Table 2-3. Caution is required when interpreting the regression coefficients. Since they are a result of a negative binomial multivariate regression, they cannot be interpreted in the same manner as coefficients would be if they were produced by an OLS regression. One of the most intuitive ways of interpreting these results is by using the factor changes in the expected count (Long, 1997). Each of the coefficients for independent variables will be interpreted below.

The steepness of the slope is found to have a negative influence on the existence of *Shorea robusta* species. The coefficient can be interpreted as follows: holding everything else constant, a one-degree increase in the steepness of the plot will result in a 2.4 (100*[exp(-.0238)-1]) percent decrease in the number of *Shorea robusta* trees. The expected relationship holds, and it is not surprising that this parameter is not statistically significant. Treks through these forests revealed very steep slopes exhibiting an abundance of vegetation. During the field visit, many species, *Shorea robusta* being one, appeared to be quite capable of establishing a foundation regardless of the steepness of the slope in these hilly areas of Nepal.

Similarly, slope aspect—measured as the degree to which the slope points to the south—is also not statistically significant. This is expected. We witnessed *Shorea robusta* on all types of terrain facing all types of directions. It appears quite capable of growing in this environment regardless of the degree to which it receives sunlight.

Slope elevation has a positive relationship with the number of *Shorea robusta* trees in a plot and is statistically significant at the 95 percent level of confidence. For every one meter increase in elevation, the expected number of *Shorea robusta* trees will increase by .4 percent.[10] This is not unexpected. Given that *Shorea robusta* can live in altitudes up to 1200 meters, and the highest plot taken in our sample is 830 meters, it is surprising that elevation has an effect at all. However, elevation captures two influences together. First, it captures the natural influence of elevation on the presence or absence of Sal trees—which in this case is theoretically quite limited. Second, it captures an aspect of optimal foraging: a degree of effort by foragers. Figure 2-2 shows that a majority of the people in this study site live in the lowlands near the river bed. I suspect that the positive influence of elevation is largely a result of foraging efforts and not as much effects of topography. As optimal foraging would predict, and as the villagers acknowledge, people tend to not want to trek from the river bed to high altitude locations to forage if they can help it. In this instance, patterns of optimal foraging are confirmed.

None of the soil variables were found to have any statistically significant explanatory relationship with the existence of *Shorea robusta* trees. This may reflect some problem in the soil data collected in this site. The soil analysis was conducted without a soil color chart. While the same people collected all of the soil data, the ability to discern soil color or texture accurately may have been lacking. The other possibility is that these variables are not influential because *Shorea robusta* is in fact the climax species of these forests: it may be robust in terms of its ability to grow in a variety of soils.

The existence of competing tree biomass is negatively related to the existence of *Shorea robusta* trees in the plot and is found to be highly significant. The coefficient, quite small, is deceiving. Its smallness reflects the measure used for competing biomass—the sum of the competing tree DBH in centimeters. A one-centimeter increase in competing tree DBH results in a less than one percent decline (-.45%) in the number of *Shorea robusta* species holding all else constant. The relationship makes intuitive sense and is what we expect: the existence of large competing trees in a micro eco-system will produce an area not receptive to *Shorea robusta* growth.

Neither of the 1 kilometer buffer variables used to quantify optimal foraging--(1) the number of households 1 kilometer from the plot and (2) the total distance of all the households within this buffer area--were found to be statistically significant. Given our knowledge of the site, this isn't surprising. These measures are inadequate in capturing the dynamics of the optimal foraging setting. First, a straight-line 1 kilometer distance doesn't adequately capture how far villagers often forage. Villagers report traveling much farther. In the dilemma over how best to operationalize this variable, a larger buffer (2 km) was considered, but if it were used nearly every household in the area would be included in the count and distance for each plot. That measure would not have been useful from a statistical point of view.

Second, and more importantly, a simple straight line distance doesn't adequately capture the human foraging decision-making in this situation. An improved method is needed to capture the distance of households from the plot using information related to trail locations. However the trail locations on the map in Figure 2-2 are insufficient and incomplete. Using DGPS to map trails would be helpful but time-consuming. Third, there is the possibility that other parameters may be affecting foraging decisions more strongly than the distance. This brings us to the trend component of the model.

The trend component of the model was included to capture both the influence of optimal foraging pressures and the institutional influences that alter human harvesting activity. Of the two trend parameters in the model, the X and Y GIS coordinates, the X was found to be significant at the 95 percent confidence level. The interpretation of this IRR for this variable requires a review of Figure 2-2. All GIS coverages are in a Universal Transverse Mercator (UTM) coordinate system. The X and Y coordinates reflect locations on this map. The Y coordinates follow the north-south axis, and the X coordinates follow the east-west axis. The origin is located in the center of the map—somewhere near the point where the Shakti and the Kayar rivers converge. The negative sign on the X coefficient suggests that as we move in an easterly direction, the number of *Shorea robusta* individuals decline We can interpret the coefficient as follows: holding all other variables constant, a one unit shift to the east produces a .06 percent decline in the expected number of *Shorea robusta* trees found in a plot.[11] As one moves across the map from west to east, the number of *Shorea robusta* trees found in plots gradually decrease. This finding provides strong evidence of the optimal-foraging and institutional induced pattern shown in Figure 2-3c.

Discussion

The results presented address both the empirical and methodological questions stated earlier in this chapter and in Chapter one. Let me address the empirical questions first.

Substantive Findings

Earlier in this paper—in the section labeled "Forests, Forest Governance, Use And Possible Outcomes"—expected forest patterns as a result of human optimal foraging and institutional induced pressures were presented. In general, it was expected that, given the forest governance structure, coupled with patterns of settlement and "natural" factors (e.g., locations of rivers) the three forests would exhibit different degrees of forest change in response to human activity over the years.

Given this, it was first hypothesized that the Kaswang forest, naturally protected by the river systems from human activities, would be the least affected by human activity. The aggregate plot data on forest species provides evidence confirming this hypothesis. Kaswang was therefore used as a reference forest and removed from the rest of the study in terms of an analysis of landscape patterns.

Second, it was hypothesized that optimal foraging coupled with limited pressures related to a weak "institutional landscape" in the area could lead to one of three possible patterns depicted in Figures 2-3a, b and c. The statistical results lend support to the third scenario. After accounting for the influence of natural forces (e.g., topography), and trying to develop well-quantified measures that capture the influence of optimal foraging using household counts and location data, a strong decreasing trend to the east was still discovered. This trend suggests that the heaviest human pressures are in the far east and northeast sections of the Latauli forest. The statistical significance of the X coordinate in the model can be explained, to some degree, by optimal foraging and the pattern of households clustering around Latauli. But close examination of the arrangement of the population over geographic space does not explain why the trend continues to the farthest points east.

Given that soil characteristics appear to have little effect in the model and that other natural environmental influences are accounted for, the only other explanation for this trend is that human foraging decisions are based on a combination of optimal foraging and institutional structure in the region. The social norms allowing villagers from Milan to harvest Latauli and the more active monitoring in the west, drive humans to forage in patterns that are different from what we would expect from optimal foraging alone. Institutional configurations alter patterns of human behavior over geographic space. This conclusion is supported by what we witnessed in the field and what villagers reported (Shrestha, 1996): many Milan and Shaktikhor residents forage in this eastern side of the Latauli forest.

These findings then, address the empirical questions posed earlier. Where has change occurred (Question *E1*)? The spatial analysis reveals that the forest depletion has been the greatest in the eastern Latauli forest and this depletion is a result of shifts in human behavior in response to institutional and community landscape configurations. What direct human actions have contributed to the change (Question *E2*)? Human foraging and forest-to-agriculture conversion. What are the indirect forces that have led humans to undertake these activities (Question *E3*)? The geographic configurations of villages comprised of wealthy families of higher social castes in the west and poorer and lower social castes in the east coupled with the stronger western monitoring mechanisms shift the "deforestation front" more toward the eastern forests and deeper into the Kayar Khola watershed. Positive or negative consequences (Question *E4*)? This shift of additional harvesting pressure on forests utilized by very poor communities has produced signs of significant forest depletion in Latuali and is surely an unintended consequence of the existing monitoring mechanisms that have been in place in this particular topography.

Policy implications (Question *E1*)? The Department of Forest's monitoring mechanism is clearly not working in this setting Their small guard units simply cannot cover the territory they are expected to Building roads to make accessibility easier is one option but not one that is feasible nor recommended. Given tight fiscal resources increasing the number of guards patrolling is probably not a feasible option either. A more appropriate step toward solving the problem of overconsumption of forest resources in the eastern Latuali forest is to devise sets of incentive structures--a new institutional landscape--that encourage the monitoring of forest resources by villagers *themselves*. Fairly recently, His Majesty's Government of Nepal has created initiatives to encourage the development of VDC forest protection committees with the idea of handing over formal property rights of the forested lands to these VDCs (Pardo, 1993). While in the field there is resistance to this by DFO officials--who fear once this hand over occurs the forested area will be even more heavily encroached--this is a move in the right direction. Only by encouraging local villager participation in monitoring will forest rules be adhered to. The DFO should try a pilot handover in this region, perhaps in Latauli, and shift their efforts toward assisting the villagers in developing effective mechanisms for developing and maintaining forest management rule systems (see Schweik, Adhikari and Pandit, 1997 for more discussion on this topic).

Methodological Implications

This study addressed the methodological question asked earlier: *How do we apply* *a spatial analysis to extract additional information about change from a one point in time geographically referenced dataset?*

While ecologists and biologists have made tremendous advances in the study of the spatial distribution of various plant species, to my knowledge, this is the first analysis of its kind that applies recent technological advances of DGPS, GIS, and maximum likelihood estimation to this effort. This study provides an example of how the inclusion of spatial information in a regression model may assist in understanding the human dimensions of forest change when longitudinal data is nonexistent. The findings support the earlier claim that a plot level of analysis may reveal findings that would not be discovered at the forest level of analysis.

Moreover, this study may also be the first of its kind to apply an institutional analysis to the study of the distribution of a particular species over geographic space. It provides a new technique for researchers to identify the influence of institutions on human foraging behavior. In any foraging setting, the first signs of forest depletion will be changes in the geographic pattern of particularly important product species as humans base their decisions and actions on the attributes of the physiographic, institutional, and community norms related to use of that forested area. After taking into consideration the natural distribution of a particular species, and accounting for physiographic influences that encourage or discourage growth, the analyst can study the existing pattern to reveal human response to past and present institutional arrangements. In this case, such an analysis provides evidence that monitoring and social norms produce shifts in foraging patterns away from traditional optimal foraging. Such evidence could not be discovered with an analysis of aggregated cross-sectional forest condition data.

Finally, it should be noted that this spatial analysis of "plots" is not limited to the study of forest natural resources. Similar techniques can be employed to study the association between natural resource condition and institutional design in other natural resource settings. In future work, for example, I intend to apply a similar technique to the study of farmer-managed irrigation resources in the same region of Nepal. Techniques such as this, can help us not only understand resource change, but also understand how institutional configurations exist over geographic space; perhaps, shedding some light into how effective institutional forms spread across a landscape or region.

Chapter 2 Endnotes

1. The research team is part of the Nepal Forestry Resources and Institutions Consortium in Kathmandu, Nepal.

2. The village names supplied by the people living in the area and recorded on the IFRI coding forms *differ* from the formal names identified on this map (see Table 1 for a comparison). To minimize reader confusion, the formal HMG map names will be used.

3. For example, Smith (1983: 632) describes the role that "exclusive control" plays in the conservation of natural resources. Feit (1973) describes rotational hunting by the Waswanipi Cree people as a method in which the size of animal population can be controlled.

4. Human stresses could be considered biotic variables (e.g., see Kozlowski, Kraemer, and Pallardy, 1991), but because of the importance of the human pressures in this study, I treat it as a separate category.

5. A winged seed.

6. For a discussion of maximum likelihood event count models, see King (1989) or Long (1997).

7. King (1990) also argues that with the computational power available in today's personal computers, researchers should now move to more sophisticated regression models that are more true to our theoretical understanding of the real world instead of using traditional techniques that were developed for computational simplicity. In addition, models that violate the OLS assumption of normality force the researcher to implement statistical tricks to ensure that the residuals behave properly. This research avoids having to use statistical tricks by investigating and specifying the correct distributional assumption and then modeling it using MLE.

8. Literature describing the natural distribution of the *Shorea robusta* species was not available.

9. Long (1997:221) summarizes this nicely in his discussion of Poisson regression models. "With this [Poisson] model the probability of a count is determined by a Poisson distribution, where the mean of the distribution is a function of the independent variables. This model has the defining characteristic that the conditional mean of the outcome is equal to the conditional variance. In practice, the conditional variance often exceeds the conditional mean. Dealing with this problem often leads to the negative binomial regression model which allows the variance to exceed the mean."

10. 100*[exp(.0040)-1] = .4

11. 100*[exp(-.0006)-1] = -.06

Figure 2-1: Study Site Location within Nepal

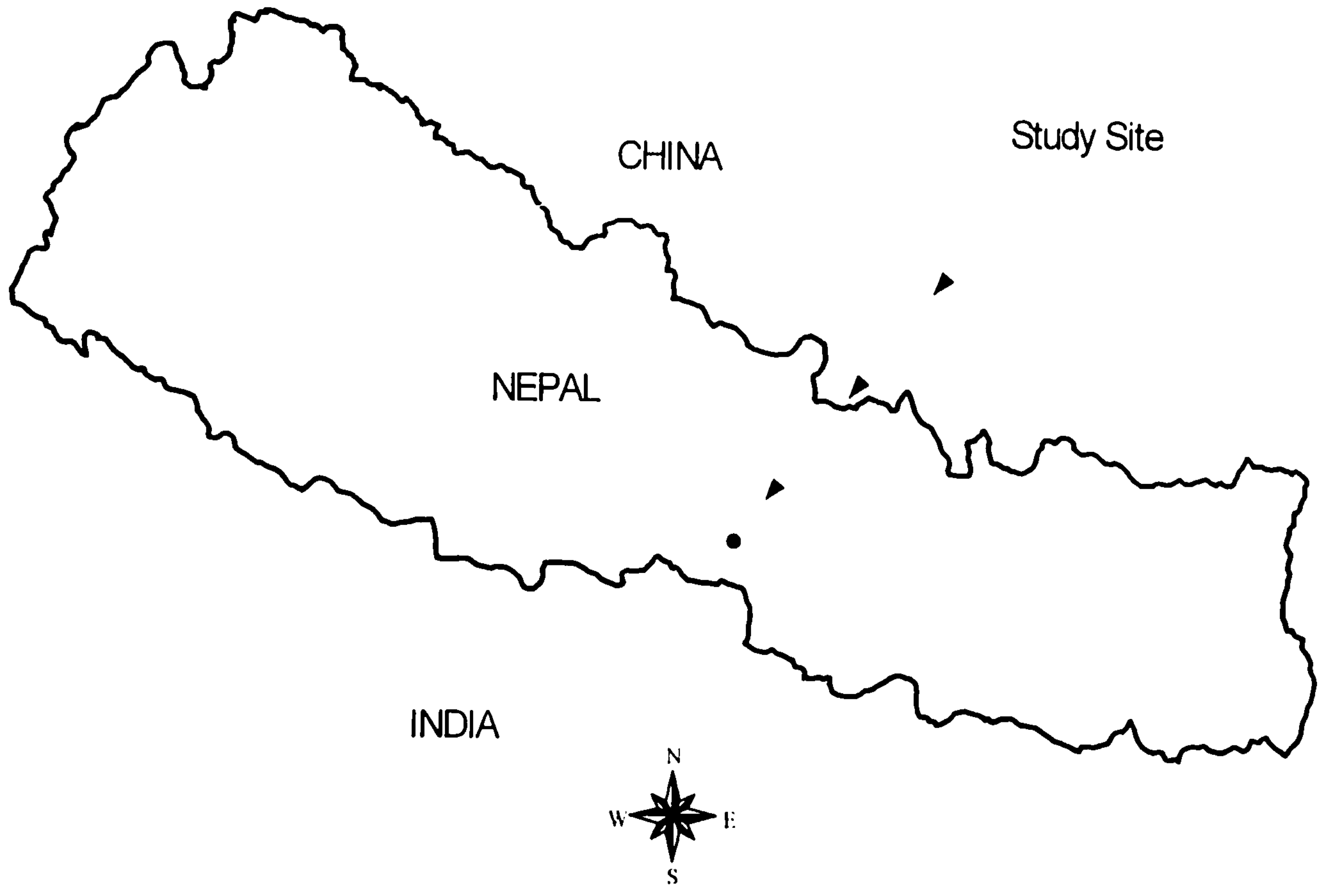
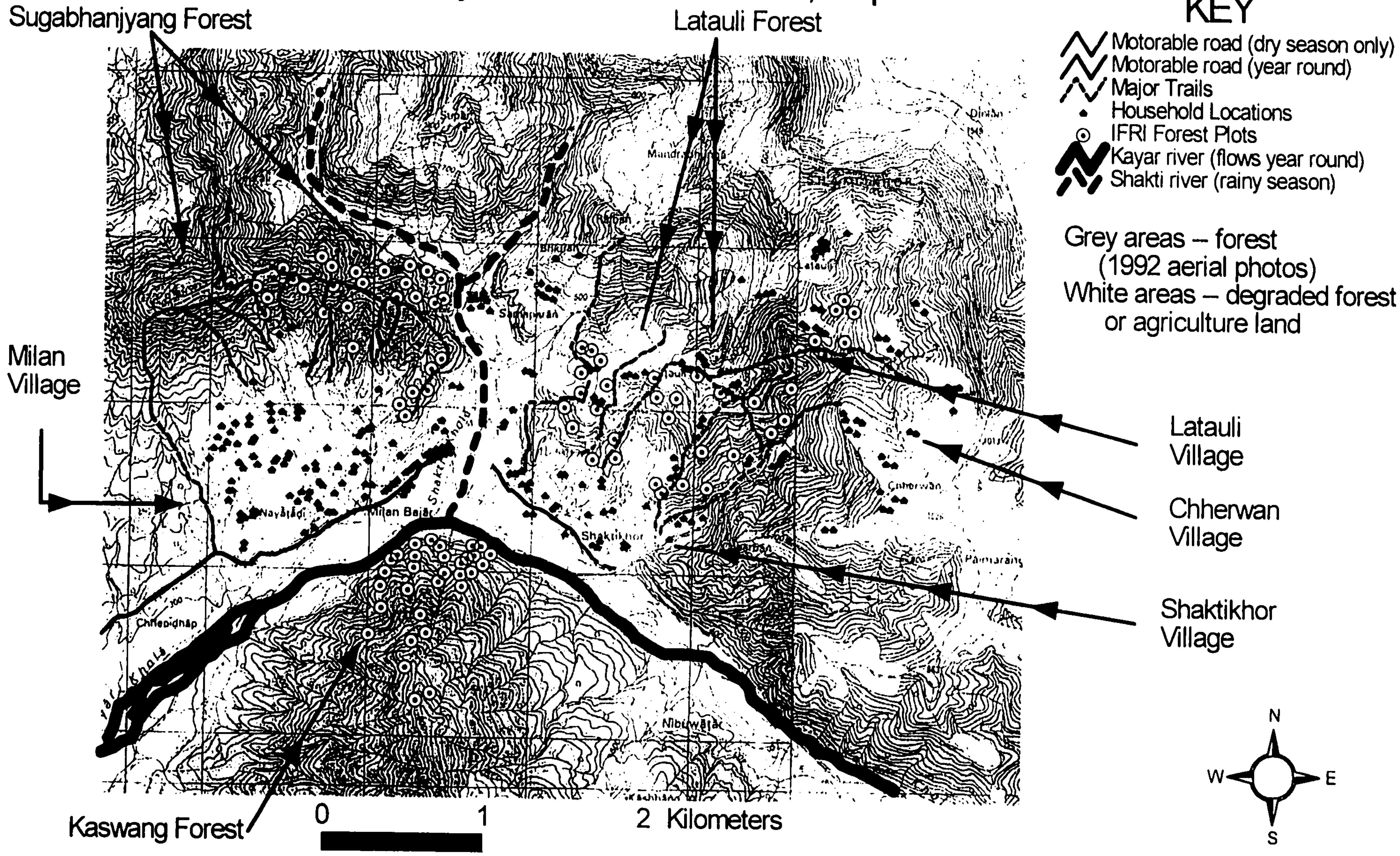


Figure 2-2: The Study Area in East Chitwan, Nepal



(Topomap source: Survey Department, His Majesty's Government, Nepal, 1994)

Table 2-1: Characteristics of the Communities in the Region (Based on villager estimates, IFRI, 1994)

Community Name (From map)	Associated village names from IFRI study	Estimated # of Households	Ethnic groups	Forests Harvested
Milan (West)	Sulitar, Kuwapani, Sinjali gaun, Bhandari gaun Sewnjaja towe, Milan Chok	110	Chepang, Chettri, Newar, Brahmin, Tamang, Gurung, Magar	Sugabhanjyang, Latauli, Kaswang (rarely)
Shaktikhor (East)	Dogara	58	Chepang, Chettri, Gurung	Latauli
Latauli (East)	Latauli, Deurali	35	Chepang, Chettri, Gurung	Latauli
Chherwan (East)	Chherwan	40	Chepang, Chettri, Gurung	Latauli

Figure 2-3a: Expected Patterns in a "No Human Influence" Scenerio

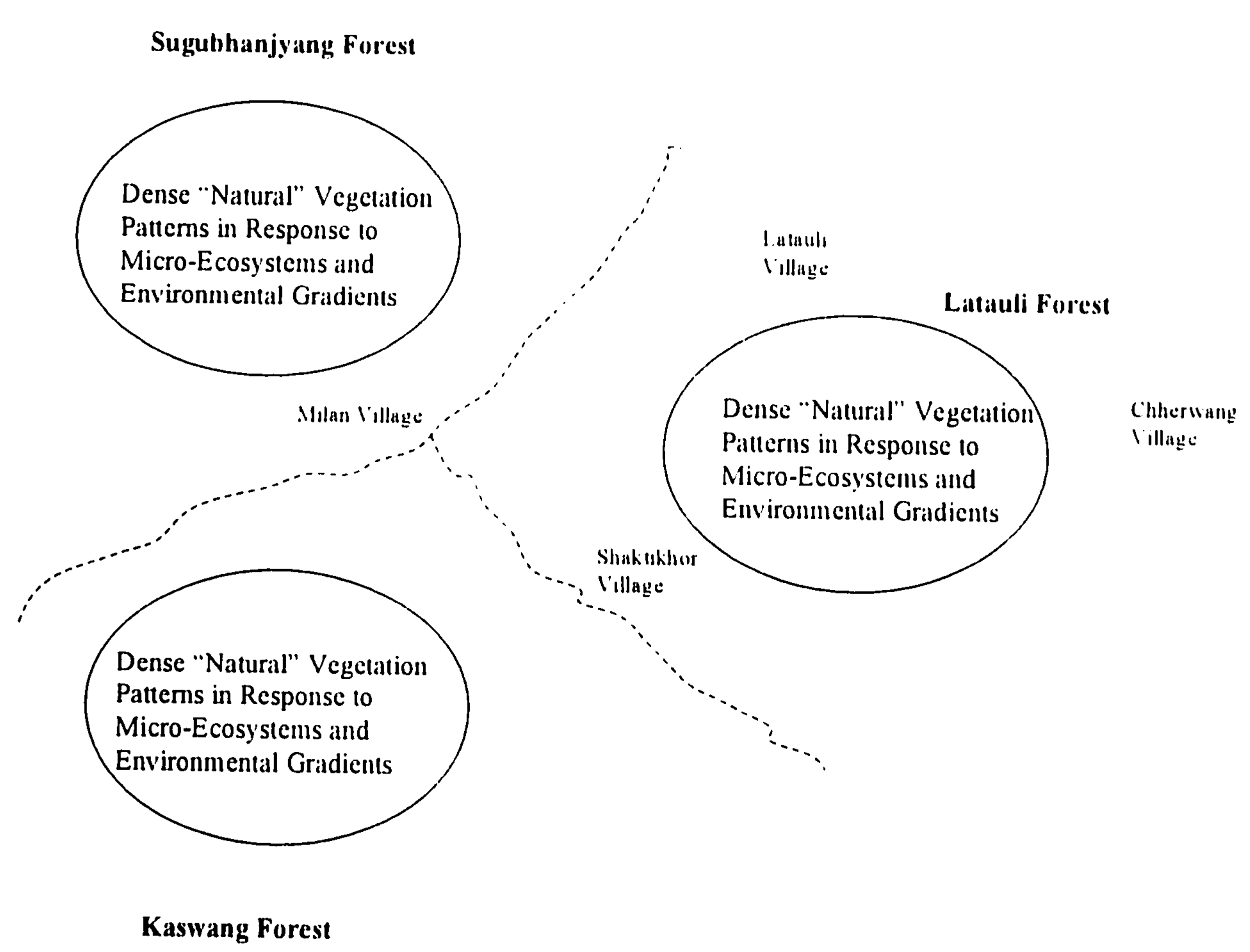


Figure 2-3b: Expected Patterns as a Result of Open Access and Optimal Foraging

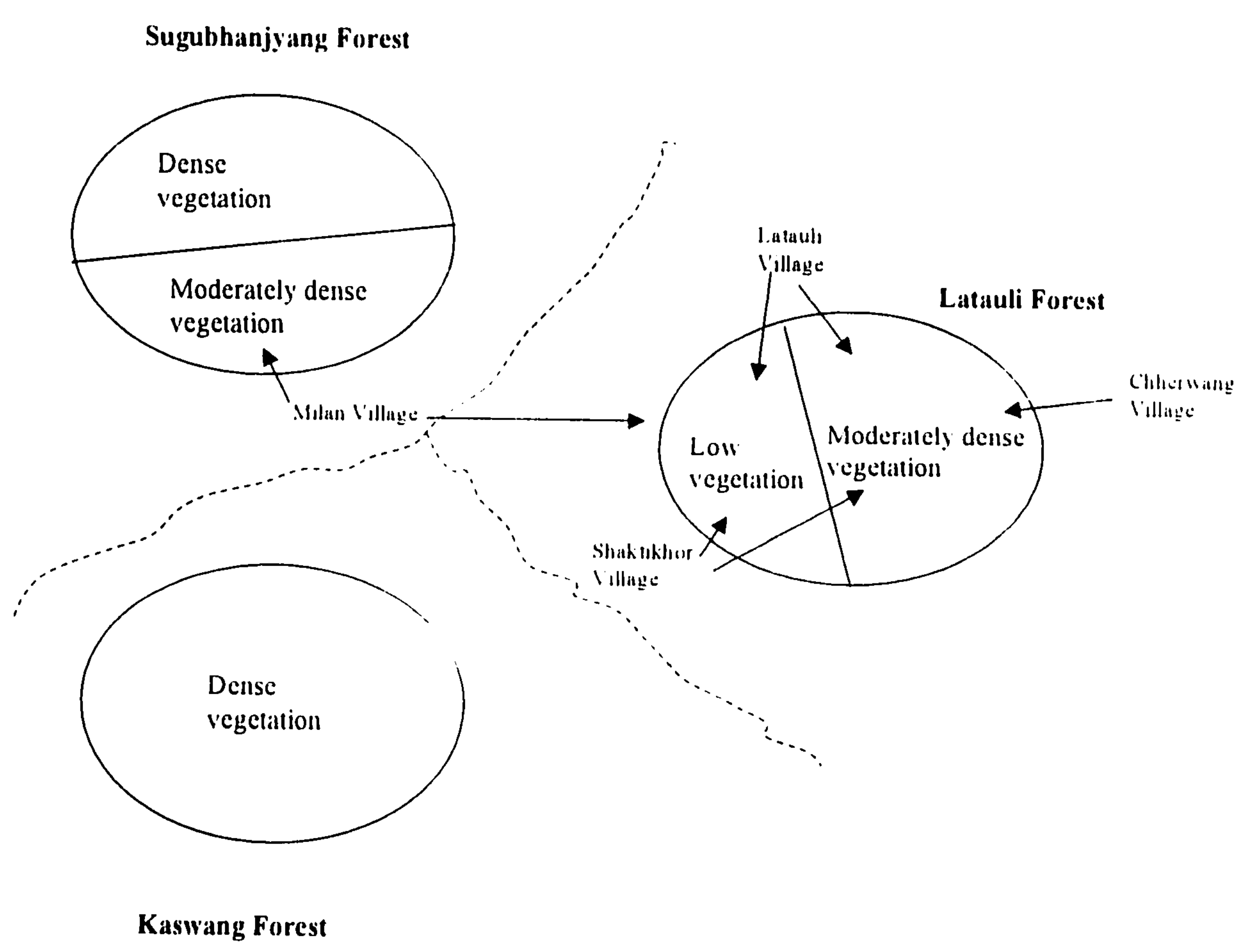


Figure 2-3c: Patterns as a Result of Optimal Foraging Combined with Institutional Influences

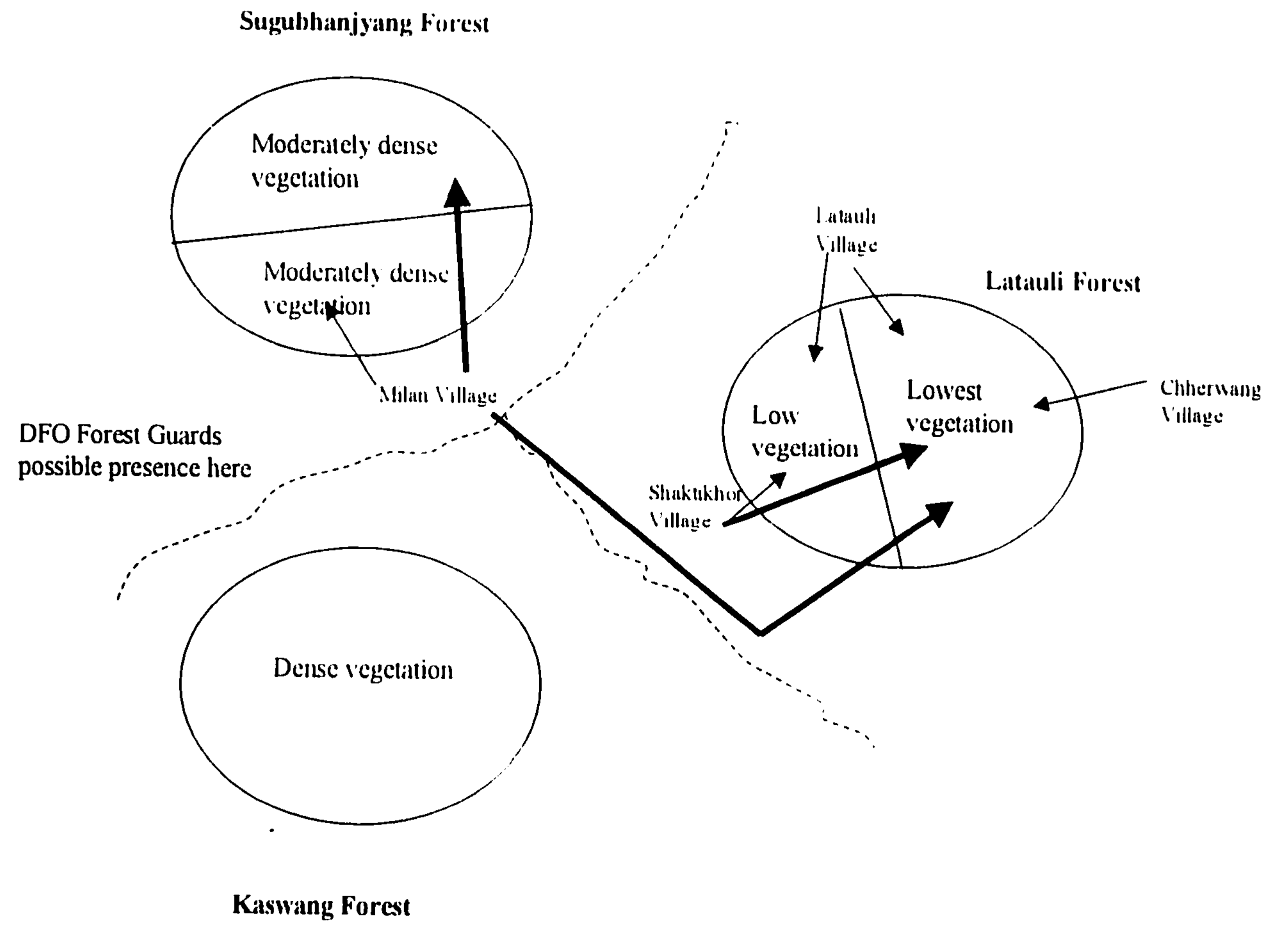


Figure 2-4: Mean DBH for Preferred Forest Product Species

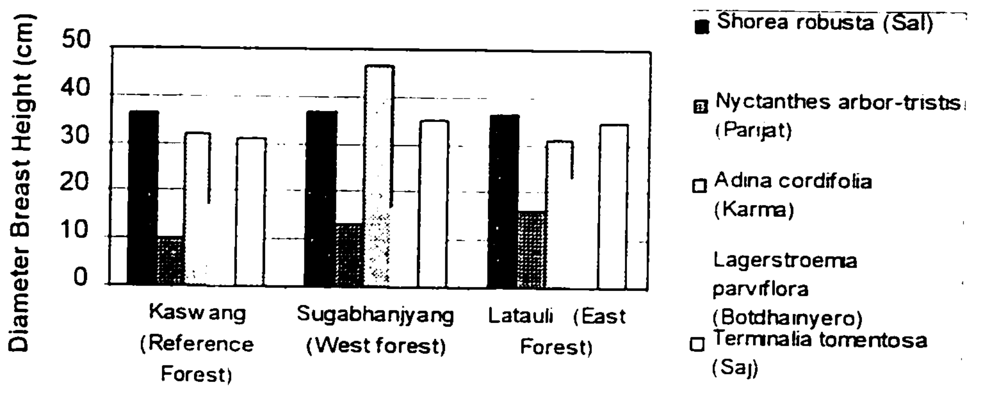


Figure 2-5: Mean Height for Preferred Forest Product Species

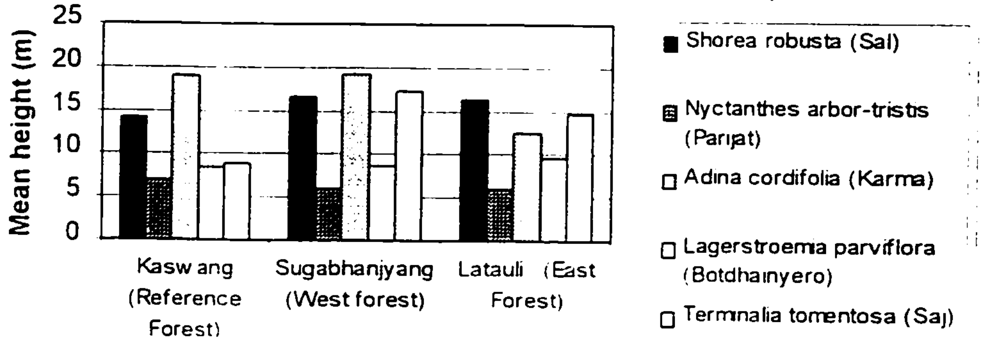


Figure 2-6: Absolute Density (trees/ha) of Important Product Species

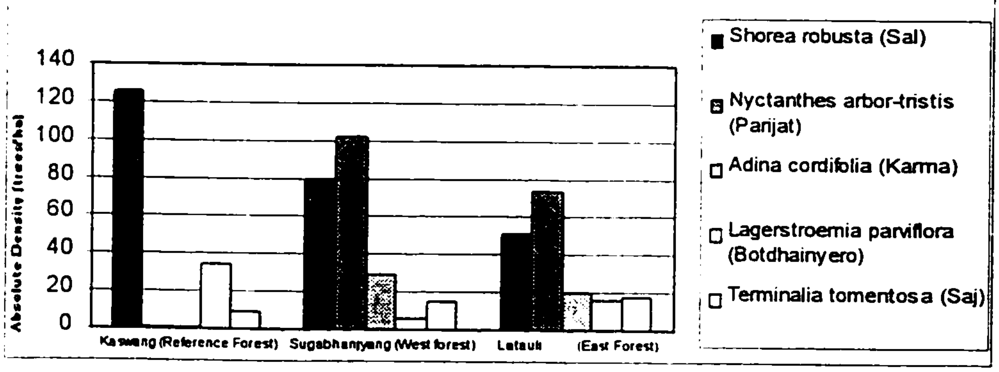


Figure 2-7: Absolute Frequency of Important Tree Species

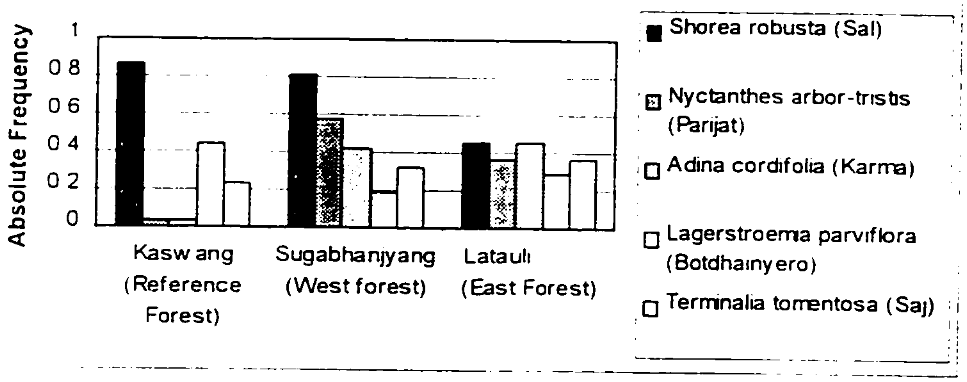


Figure 2-8: Dominance of Important Tree Species (Total ba/ha)

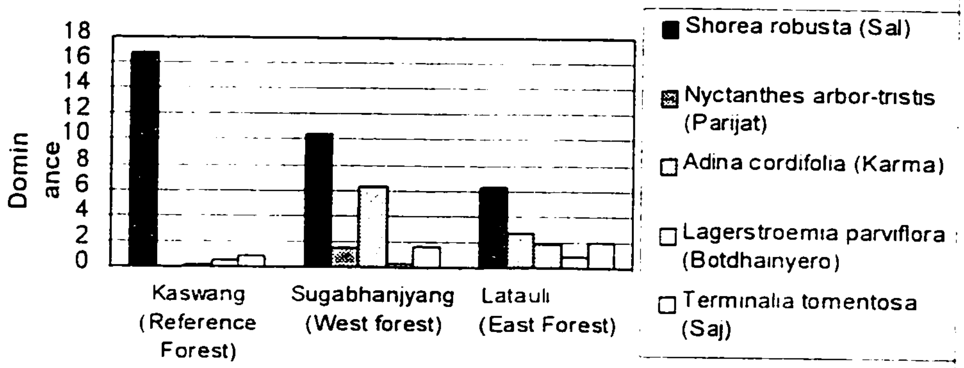


Figure 2-9: Importance Values for Preferred Tree Species in the Forests of the Shakitkhor Study Area

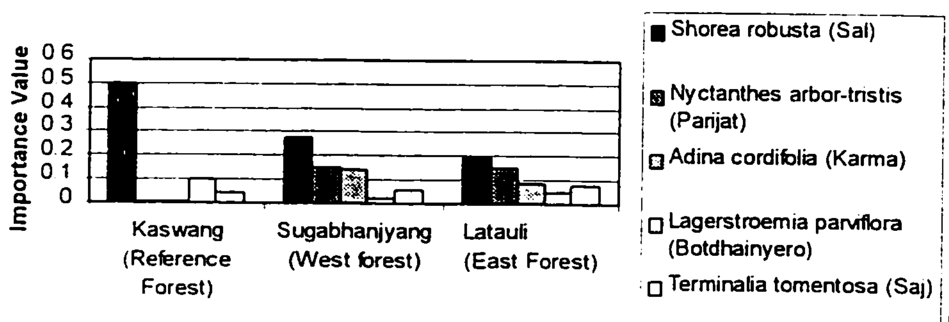


Figure 2-10: The "Species Density" Model

Number of *Shorea robusta* trees in a forest plot = F (Abiotic stresses, Biotic stresses, Human stresses)

Abiotic stresses:

- Slope steepness
- Slope aspect
- Elevation of the plot
- Soil nutrients, moisture and physical composition
- Other natural disturbances

Biotic stresses:

- Competitor tree species
- Existence of neighboring *Shorea robusta* seed trees
- Animal grazing (wild or domesticated) patterns

Human stresses:

- Plot location (ease of access to plot, optimal foraging)
- Property rights and rules-in-use for species in the plot
- Monitoring: Likelihood one will get caught while undertaking illegal harvesting within the plot
- Sanctioning: The level of punishment a harvester might be subjected to for breaking a harvesting rule in this plot

Figure 2-11: Three Example Forest Plots with 1 km Distances Identified

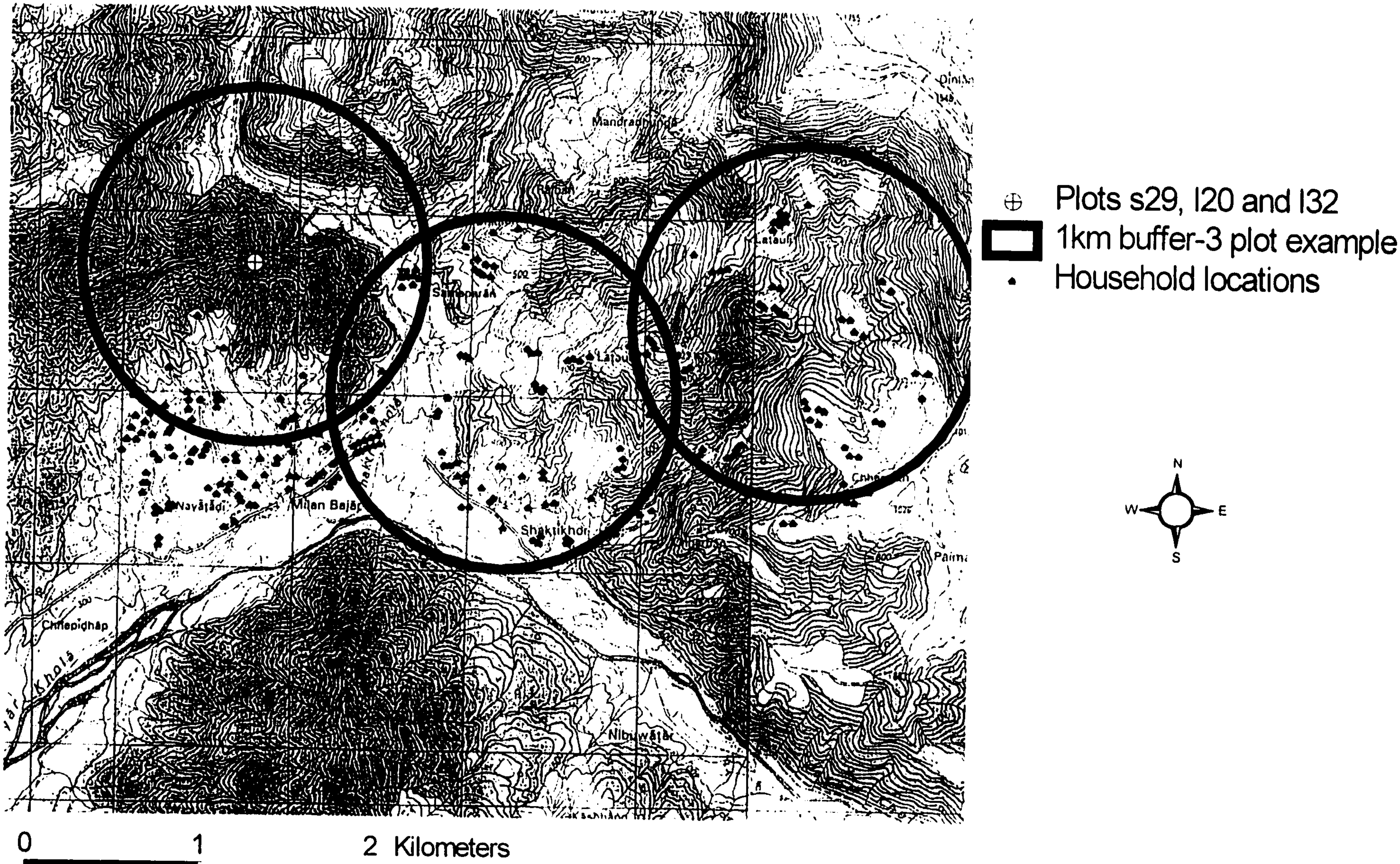


Table 2-2: Chi-square Test of the Index of Dispersion of *Shorea robusta* Species in the Kaswang Forest

Average Number of Individuals per Plot	5.968
Number of Plots	31
Variance	12.644
Index of Dispersion (variance/mean ratio)	2.119
X^2 statistic [$X^2 = ID(N-1)$]	63.562 †

† Significant at the 99% level of confidence.

Table 2-3: Negative Binomial Coefficients for Three Foraging Models (Dependent Variable Number of *Shorea robusta* Trees in Forest Plots) *

	Independent Variables	Coefficients	IRR
Abiotic Factors	Slope steepness	-.0238 (.0149)	.9764
	Slope aspect	.0290 (.1277)	1.029
	Elevation	.0040 ‡ (.0016)	1.004
	O horizon (humus layer depth)	-.2120 (.1368)	.8089
	A and B horizon depth	-.0108 (.0368)	.9893
	A and B horizon color	.0729 (.0885)	1.077
	A horizon texture	-.1993 (.2174)	.8193
Biotic Factors	Competing tree biomass	-.0045 † (.0017)	.9955
Human foraging (plot accessibility measures)	Number of households within 1km	.0038 (.0125)	1.004
	Average Distance of households w/in 1km to plot	.0006 (.0020)	1.001
	X coordinate	-.0006 ‡ (.0003)	.9994
	Y coordinate	.00003 (.0009)	1.000
	Intercept	-.1099 (3.059)	----

Negative Binomial log-likelihood: Model 1 -109.773; Model 2 -107.326; Model 3 -107.094 n = 66
*Numbers in parentheses are standard errors.
† Significant at the 99% level of confidence. ‡ Significant at the 95% level of confidence.
§ Significant at the 90% level of confidence.

Chapter 3

FOREST CHANGE IN INDIANA:
RESEARCH QUESTIONS, POLICY RELEVANCE AND PLAN OF STUDY

Forest Change and Forest Policy in Indiana

Forest policy debates in many tropical and/or so-called "developing"[1] countries such as Nepal have concentrated largely on investigating alternative measures to slow or halt the process of forest loss and conversion. The problem of deforestation does not just occur in the developing world, however. There are many "developed" countries that are also faced with difficult forest policy issues related to the loss of forest resources. For example, debates continue to rage over both the extent to which timber harvesting continues in old growth areas of the Pacific Northwest of the United States (Langston, 1995) and Canada (Thompson, et al., 1992) and over the appropriate management methods applied (Kimmins, 1992).

Yet over the last century there are significant land areas that have either significantly slowed or essentially ceased deforestation in terms of a net loss in forest area. In fact, many U.S. states have experienced a net gain in forested area over the last century; they have been subject to the opposite processes of reforestation and afforestation. Many states, particularly ones in the eastern and the midwestern United States, possess a history of extensive land clearing (e.g., for agriculture) in the nineteenth century that then was followed with agriculture land abandonment and secondary and mature[2] regrowth over the twentieth century (Spurr and Barnes, 1992).

The state of Indiana exhibits such a history. This history is summarized in Figure 3-1. Prior to European settlement it is estimated that 87 percent of the state was forested (Le Master and Rans, 1997: 13)—roughly 20 million acres (Jackson, 1997: xvii). Throughout the period of settlement, forests were cleared for agriculture and development. The peak of forest clearing probably occurred around 1930 (Le Master and Rans, 1997) and of the original 20 million acres of forest cover fewer than 2000 acres of virgin old growth forests remain today (IDNR, 1997). Beginning with the Great Depression in the 1930s Indiana experienced the process of forest regrowth primarily due to farm abandonment (Le Master and Rans, 1997: 13). Spencer *et al.* (1990) estimate that the area designated as "forest land"[3] in Indiana rose from 4 million acres in 1967 to 4.4 million acres in 1986 and suggest that this net increase can be attributed to "reversion of wooded pasture and improved pasture to timberland" (p. 1). Most of these regrowth areas would be classified now as secondary or mature forest landscapes.

Figure 3-1 about here

This discussion should not leave the reader with the impression that these secondary and mature forested landscapes do not continue to change—they most certainly do. Recall the description provided by the framework presented in Figure 1, Chapter 1: forest vegetation is altered in response to natural forces (e.g., natural successionary forces and animal and weather disturbances) and change in response to anthropogenic actions. Timber harvesting, silviculture management and other landscape modifications such as forest conversion for agriculture and development continue in these landscapes, but many of their effects may be less dramatic in comparison to some countries subject to heavy deforestation activities. In sum, it is expected that forest land in Indiana today fluctuates in geographic extent as the last part of the time line in Figure 3-1 represents. Some agriculture land parcels continue to be abandoned and convert back to forest cover Other forest areas continue to be are converted into agriculture areas or directly into some other development-related land cover.[4] The last survey of Indiana forests, conducted in 1986, reports that overall forest area continues to increase in the region (Spencer, *et al.* 1990). The results from the recent 1996 Indiana forest survey have not yet been published, so whether this trend continues is unclear.[5]

In instances, such as in southern Indiana, where physical landscapes are undergoing afforestation and landcover fluctuation, the policy questions related to forest management have, at least in one sense, become more complicated. The problem has shifted from the relatively straightforward *conceptual* policy problem of halting deforestation to the more complicated *conceptual* policy problem of how to best balance competing and multiple uses and services that primary and secondary growth forest areas provide. Policy-makers face the problem of how to best balance economic development interests (e.g. timber sales and forest landscape development) with watershed (riparian zone) protection, habitat and biodiversity conservation and enhancement (issues related to forest fragmentation), and mature forest (and to a smaller degree old growth) and wilderness preservation.[6] To restate this in another way that is helpful for thinking about spatial and temporal analysis: the focus of debate has moved from questions related to the *extent and rate of forest loss* to questions related to *temporal change in the patterns of forest vegetation–the size, shape, composition, condition and temporal stability of forested landscapes.*

A very brief reflection on the history of the changing forest philosophy in the United States over the past 150 years lends credence to these statements. In the mid-eighteenth century, Alexis de Tocqueville (1945: 74) commented on the significant forest to agriculture conversion being undertaken at the time when he commented that the citizenry "march across the swamps, turning the course of rivers, peopling solitudes and subduing nature." Slowly however, over the late nineteenth century and throughout the twentieth century, an awareness in the multiple functions and services forested lands provide grew into the American psyche. This began with events such as the cataclysmic flooding and fires that occurred in the late nineteenth century in Michigan, Wisconsin and the New York State Appalachian region (Brame and Henderson, 1992).

These environmental disasters led some to the realization that the American wilderness was no longer a threat to human survival but rather that humans were capable of altering ecosystem services and threaten both vegetation and wildlife habitat. Humans realized that significant anthropogenically driven denudation of forests could in fact alter watershed and other ecosystem services. Further, Nash (1982) describes another utilitarian revelation during this period: the gradual shift in mind set in the U.S from one where humans need to "tame" the wilderness and covert it to civilized places to one where wilderness was required for a psychological refuge from the pressures of civilization: what we now typically call "recreation." The general thinking in the U.S. over the late nineteenth and twentieth centuries shifted more toward a "stewardship ideal" and a multi-use, multi-service mindset about the utility of forested landscapes. To a lesser degree the emphasis (or at least an awareness) of the intrinsic right of non-human life to exist was also included in the thinking of some forest property managers (see for example, Leopold, 1949 [1989]). Though individual human-forest philosophies differed then (as they do now), the general and gradual change in thinking toward a "stewardship" ideal is revealed in many of the prominent writings by scholars, and policy-makers of the late nineteenth and early-to-mid twentieth century; authors such as Ralph Waldo Emerson and Henry David Thoreau, John Muir, Theodore Roosevelt, Gifford Pinchot, Aldo Leopold and others.

The present day forest policy debates in Indiana reflect this evolution in philosophy related to human-forest relationships. Many forested areas are still subject, to some degree, to logging. Indiana forest resources support several industries producing some type of wood products: taken together, the veneer, hardwood lumber, furniture and cabinet industries comprise one of the largest employers in the state (Le Master and Rans, 1997:1). However, the debates continue over these now "traditional" concerns over harvesting versus the recreational and ecological services forests provide (e.g., Mahler, 1997; Jones, 1997).

Further, over the last three decades or so, forest policy in the public sector has become an even more complicated balancing act of weighing these traditional concerns with a number of more recently developed more detailed or alternative and oftentimes rival interests (Kimmins, 1992; Sample, 1994). This is in part due to the advances we have made in recent decades related to the physical sciences. Conservation arguments have become more specific including concerns such as the protection of vegetation along riparian areas (e.g., Jones, 1997), the preservation of biodiversity (Anderson, 1993) and "genetic libraries" (Meadows, 1990), and the perpetuation of forest biomass growth to help reduce global atmospheric concentrations of carbon (Faeth, Cort and Livernash, 1994; Cubbage *et al.*, 1992). To complicate matters further, in addition to being subject to a broader set of forest uses and services to consider, today's forest property managers are also subject to increasing scrutiny over what some would consider "finer" or "micro" management activities. For example, very recently in Indiana there has been tremendous public debate over whether sets of trees damaged by a severe weather disturbances should be salvaged harvested or left to naturally decompose (Mahler, 1997; Hinnefeld, 1996).

In states like Indiana, public and perhaps to a lesser degree private land managers have been struggling with how to deal with the wide variety of values and interests about the use of their forested properties as well as the increased scrutiny of their actions. Many property managers consider a spectrum of actors' preferences, interests and values in their deliberations over of general forest policy and more specifically direct actions they undertake on a particular parcel of a forested landscape. Koontz (1997) organizes these preferences into three categories: commodity, preservation and recreation and argues that these preferences have differences in their *potential* to alter forest landscape conditions. We can lay these general preference categories side by side to create a spectrum based on their potential to alter a forested landscape. At one end of this spectrum are actors whose preferences lean toward commodity and economic development type uses of a forested landscape. Actors with heavy commodity interests have substantial potential to alter forest conditions (Koontz, 1997: 18). At the opposite end of this spectrum are "preservationists" whose preferences are more heavily weighed toward the protection, conservation and minimal human disturbance of forested areas. Actors possessing heavy preservation interests have significantly lower potential to disturb forest conditions (Koontz, 1997: 20). I would argue that actors with heavy recreational interests fall somewhere in between these other two groups in terms of their preferences toward alteration of forested landscapes.

To summarize, the forest policy environment in these vast areas of the United States where secondary and mature forest is dominant and reforestation and afforestation processes have occurred no longer focus on issues related to deforestation but rather on issues related to "economic development" and forest "preservation" or "stabilization." At the heart of these debates are questions related to biodiversity, wildlife habitat, wilderness and old growth preservation and watershed protection.

But the information and knowledge gaps presented in Chapter 1 slow our progress toward the crafting of policies and management practices that adequately address these issues. Even in the United States, where sizable budgets are appropriated for forest management, these information and knowledge gaps exist:

> *Information Gap 1: In a majority of circumstances, we lack baseline inventory data on the condition of the natural resource. In cases where such data exists, it is either not georeferenced, or it is georeferenced in some aggregate form.*
>
> *Information Gap 2: In most circumstances, we lack longitudinal, georeferenced data on natural resource condition.*
>
> *Information Gap 3: In nearly all circumstances, we lack longitudinal, georeferenced data about the <u>institutions</u> that have governed the natural resource.*
>
> *Knowledge Gap 1: We possess an incomplete understanding of the longer term effects direct human action has on natural resource condition.*
>
> *Knowledge Gap 2: We lack knowledge on variables that act as indirect forces that lead to changes in natural resource landscapes.*
>
> *Knowledge Gap 3: We lack understanding about how changing scale influences our findings related to human action and natural resource landscapes.*
>
> *Knowledge Gap 4: We do not adequately understand the relationships between the information provided by satellite images and the landcover on*

the ground. Moreover, we do not have well worked out methods on how to apply them to study the human dimensions of environmental change

Because of these gaps in our information and knowledge, we have not been able to monitor, at least very well, how stable or changing institutional landscapes affect human decision-making and action and how this leads to fluctuation or stability in the physical natural resource landscape.

Let me provide an example of how this describes precisely the issue faced by natural resource managers in the State of Indiana and surely elsewhere in the United States. Recently, in Indiana, state "Heritage Trust" and "Forest Legacy" programs have been initiated that seek to identify environmentally important forest lands that are in danger of being destroyed as a result of development activities (e.g., IDNR, 1998a; 1998b). In the Heritage Trust program, the State actually purchases important forested areas for state management (IDNR, 1998a). In the Forest Legacy program, development rights only are purchased from the private owner. The owners still retain other rights to the land area (IDNR, 1998b). Two of the significant challenges facing public officials who manage these programs are: (1) how to identify important ecosystem areas and (2) how to determine whether they are under the threat of development. Understanding where the limited funds in these programs should be targeted is of significant importance to program officials (Fischer, 1998).

While state officials may use the best available information they have to identify endangered areas, their efforts are often hindered by the lack of available information on the physical landscape change itself—the deforestation front or development "fringe"—and how human actions and decisions have led to such changes. In other words, better information is needed on how incentive structures influence the decisions and actions of both private and public property managers and how these actions manifest themselves in physical landscape change.

Remote sensing and GIS tools are being used to assist in these land protection decisions. For instance, recent national wetlands inventory maps of Indiana (USFWS, 1998) have been developed using relatively fine scale aerial photographs taken in the 1980s. Similarly, state wide landscape inventory maps for Indiana have been produced for gap analysis (see for example, Scott, *et al.*, 1993) using Landsat TM images for one point in time (IGAP, 1998). But to date, few have taken advantage of the opportunities powerful GIS and remote sensing software bring to analyze change in a time series of satellite images and how these patterns are associated with human action. Even fewer studies, if any, have attempted to link incentive structures to patterns found in temporal sets of satellite images.

Objectives of this "Temporal Analysis" Study

The primary objective, then, of the second study in this dissertation is to investigate linkages between institutional landscape structure, human decisions and resultant forest change as captured by temporal sets of multispectral satellite images. Through such an exercise, I hope to contribute toward the filling in of the information and knowledge gaps presented above.

Ideally, I would study the full range of institutional structures falling in the general categories of private, not-for-profit and public property regimes, and link this to change or stability witnessed in a broad geographic physical landscape. But this is much too large an endeavor for any one single dissertation. I therefore turn to a subset study, comparing the incentive structures, actions and outcomes in two publically managed lands: one state and one national forest.[7] I choose public forests for this study for three reasons: (1) information about where and when human actions have taken place are relatively well documented in these settings and often have associated field vegetation inventories available; (2) records of the institutional landscapes of property managers in public settings are often well documented, including their geographic histories; and (3) a great deal of attention and concern is given to how public forests are managed, and what outcomes or forest conditions are produced. This study will shed some light about stability of public forest landscapes over time.

Similar to the spatial analysis study presented in Chapter 2, I ask again the same set of four empirical questions:

> *E1) Where has change occurred in the physical landscape of public forest resources in southern Indiana and where has it remained stable? How are these linked to important policy issues?*
>
> *E2) What direct human actions have taken place over time that contribute to the change we witness in these public forests?*
>
> *E3) What are the indirect forces—the configurations of community and institutional landscape attributes—that have led humans to undertake these activities?*
>
> *E4) What temporal patterns in the community and institutional landscapes appear to have led to resource conditions we might consider as "positive" or "negative"?*

These questions require some measurement of forest landscape condition that has been taken over time. Recall from discussions in Chapter 1, that over the last quarter of a century advances in remote sensing and digital storage technologies have amassed a tremendous temporal and geographically referenced dataset on natural resource change for many locations in the world. A number of scholars interested in human-environment relationships have undertaken studies that utilize these data sources of forest and landscape condition (E.g., Green and Sussman, 1990; Moran, Brondizio and Mausel, 1994a, 1994b; Sader, 1995). The existence of such spatio-temporal datasets mean that the first two information gaps (aformentioned in this chapter) are beginning to close. We possess methods of collecting "landscape complete" longitudinal measures that we can use to help quantify our forest condition dependent variable. This study will employ a longitudinal set of satellite images to investigate these empirical questions.

To do so, this part of the dissertation, then, must also address the latter three methodological questions presented in the first chapter but worth repeating here:

> *M2) To what degree can the longer temporal extent Landsat MSS data help in understanding change in forested landscapes over time?*
>
> *M3) How can we tease out the effects of human activities from patterns in temporal sets of satellite imagery?*
>
> *M4) To what degree does the analytic technique spectral mixture analysis (Adams, et al. 1994) help to understand change that is captured by relatively coarse resolution MSS imagery?*

Study Location

To investigate these empirical and methodological questions, this study focuses on public forests in a five county region of south-central Indiana: an area Homoya (1997:159) refers to as the "Brown County Hills." It is a predominantly unglaciated area with a principal bedrock comprised of siltstone, sandstone and shale. Over the ages, this bedrock has become deeply eroded producing valleys, ravines, ridges and hills (Homoya and Huffman, 1997).

The forest vegetation in these hills are relatively diverse (Table 3-1). "Oak-Hickory" stands, defined as forested areas where oaks and hickory species either singly or in combination comprise 50% or more of the trees (Barrett, 1980:118), are prominent. These stands are capable of existing on diverse topographies, ranging from deep, mesic (wet), loamy, productive soils to xeric (dry), ridgetops with shallow soils (Ibid.), but often, they are found on dry, south-facing slopes in this region (Homoya and Huffman, 1997). Better sites with deep, mesic soils are often occupied by a diverse mixture of northern hardwood species. Beech and Maple are important species in these settings and these types of stands are often classified as such (Barrett, 1980). In some settings, largely in bottomlands and flood plains, Elm-Ash type forest stands can also be found. These typically are found in long narrow strips along streams in the region (Ibid.).

Table 3-1 about here

This study region was selected for three reasons. The first reason is that it encompasses the largest area of publically owned forested land in the state of Indiana. Forests in the region, like most everywhere else in the United States, are governed by a diverse set of property regimes and institutional forms. Much of the forested are in the region falls under private property. However, in this southern half of Indiana there exists a significant public sector ownership at the state and national level, making it an appropriate area to study, both for this dissertation and for a continued longer term study comparing private and public forest management and landscape change.

The second reason for selection of this area is more technical in nature. In order to look at landscape change as it is captured by Landsat satellite images, it makes good sense to try and maximize the temporal extent of image coverage. The Landsat satellite system began its service in 1972 and continues to this day. Five workable satellites have been employed throughout Landsat's lifetime. When the fourth satellite was launched, Landsat 4, in July 1982, its sun-synchronous orbit was shifted to a lower altitude that differed from the orbits of the previous Landsat satellites 1, 2 and 3. As a result, the "footprint" of the images that were taken by the later Landsat 4 and 5 shifted in location when compared to the footprints of images taken by the earlier Landsat satellites. Thus, in order to maximize the temporal range of the study, five counties that fall within the overlap of these footprints were selected. A diagram of this region, along with the footprints of the two different Landsat orbits, are shown in Figure 3-2.

The third reason is because of data availability. The Indiana Department of Natural Resources Division of Forestry gave me full access to their records in the region. This is particularly important for the work done in Chapter 6.

Plan of this "Temporal Analysis"

The rest of this study takes on the following organization. First, a theoretical discussion is presented which focuses on the types of actors involved in public forest ownership, governance and management, the types of incentive structures they face, and the types of activities they are expected to select. Expected direct actions need to be based on the theoretically-derived sets of incentives and constraints. It is assumed that these actors consider these incentives in some informal cost/benefit calculus and make decisions based on their internal calculations. With this theoretical foundation established, general sets of hypotheses on human incentives, human actions, and outcomes can be developed that can then be empirically tested. Chapter 4 is devoted to this endeavor: to generate general direct action hypotheses for property managers and actors working in one state and one national forest.

Next, the empirical research questions posed above require the definition of one or more dependent variables that capture the condition of a forested landscape. In this instance, the dependent variable, forest landscape condition, will be quantified by applying a relatively new analytic technique labeled "spectral mixture analysis" or SMA (Adams et al. 1986, 1993, 1994; Smith et al 1990) to a time sequence of four Landsat MSS scenes. In addition, effort needs to be made to investigate the sensitivity of relatively coarse resolution MSS imagery and SMA products. In other words, verification must be made to ensure that the course spatial resolution of MSS does, in fact, pick up information related to action taken by property managers and their agents on the ground. For instance, if we wish to understand how direct actions such as "group selection" impact forest condition as measured by satellite reflectance, we need to verify that these activities are recorded by the satellite sensors with relatively course spatial resolution. Chapter 5 provides an overview of Landsat MSS data and spectral mixture analysis. Chapter 6 then analyzes known locations of direct actions in one reference forest and investigates the sensitivity of Landsat MSS resolution toward identifying these activities. This endeavor identifies the spectral look or "trajectory" of several forest activities under several different topographic regimes. In short, Chapter 6 develops a forest condition "temporal spectral trajectory library" for known forest activities using a reference forest in the region.

Once the sensitivity of the Landsat MSS data and the results of spectral mixture analysis are known, Chapter 7 expands the spatial scope of the study and undertakes an analysis of temporal dynamics of other publically managed forested landscapes in the region. This chapter, in essence, strives to support or reject the hypotheses created in Chapter 4 by comparing trajectory patterns found in these new forested areas to the set of library patterns identified in the reference forest of Chapter 6. Findings are discussed and future research is presented.

With this overview now outlined, let us now turn to a discussion of the incentive structures faced by public forest managers in the Indiana context.

Chapter 3 Endnotes

1 One source includes Africa, Latin America, China and parts of Asia (e.g., Nepal) as members of the "developing world" category (World Resources Institute, 1986).

2 The definitions provided by Duffy and Meier (1992) are useful in this context. The term "primary" is used to "describe forests that have never been clear-cut and that have little or no evidence of past human activity. Such forests may have been grazed, they may have experienced limited exploitation of valuable tree species, and their floors may have been burned by Amerinds and European pioneers. Primary forests contain abundant downed timber in varying states of decay, standing dead trees, and live trees in a range of sizes." The term "secondary" is used to describe forests "that have developed after the previous forest was extensively logged or clear-cut." Duffy and Meier add a third term, "mature" which they use to refer to "secondary forests that have existed longer than the normal harvesting rotation practiced by foresters on that particular forest type."

3 Spencer et al. (1990: 40) define "forest land" as "land at least 16.7 percent stocked by forest trees of any size, or formerly having had such tree cover, and not currently developed for nonforest use.

4 For instance, one public forest official mentioned that timber companies and developers are working together to buy forested areas, cut the forest down for timber, and then move in and develop it. This was surprising, for most think that the conversion in south central Indiana is more gradual, with agriculture land eventually being developed as urban sprawl continues in some areas.

5 In 1996 and 1997 the latest statewide Forest Inventory was conducted by the Indiana DNR and the U.S. Department of Agriculture's Forest Service. Their reports have not yet been published.

6 For a useful summary of current forest policy issues in the state of Indiana, see Le Master and Rans (1997).

7 I should note that my colleagues and I have been embarking on such a study of non-industrial private forest owners in Indiana. For the results of one pilot project, see Koontz, Carlson and Schweik (1998).

Figure 3-1: Time line of Forest Clearing and Forest Regrowthin Indiana
(Estimated acreage taken from Parker, 1997, Jackson, 1997 and IDNR, 1997)

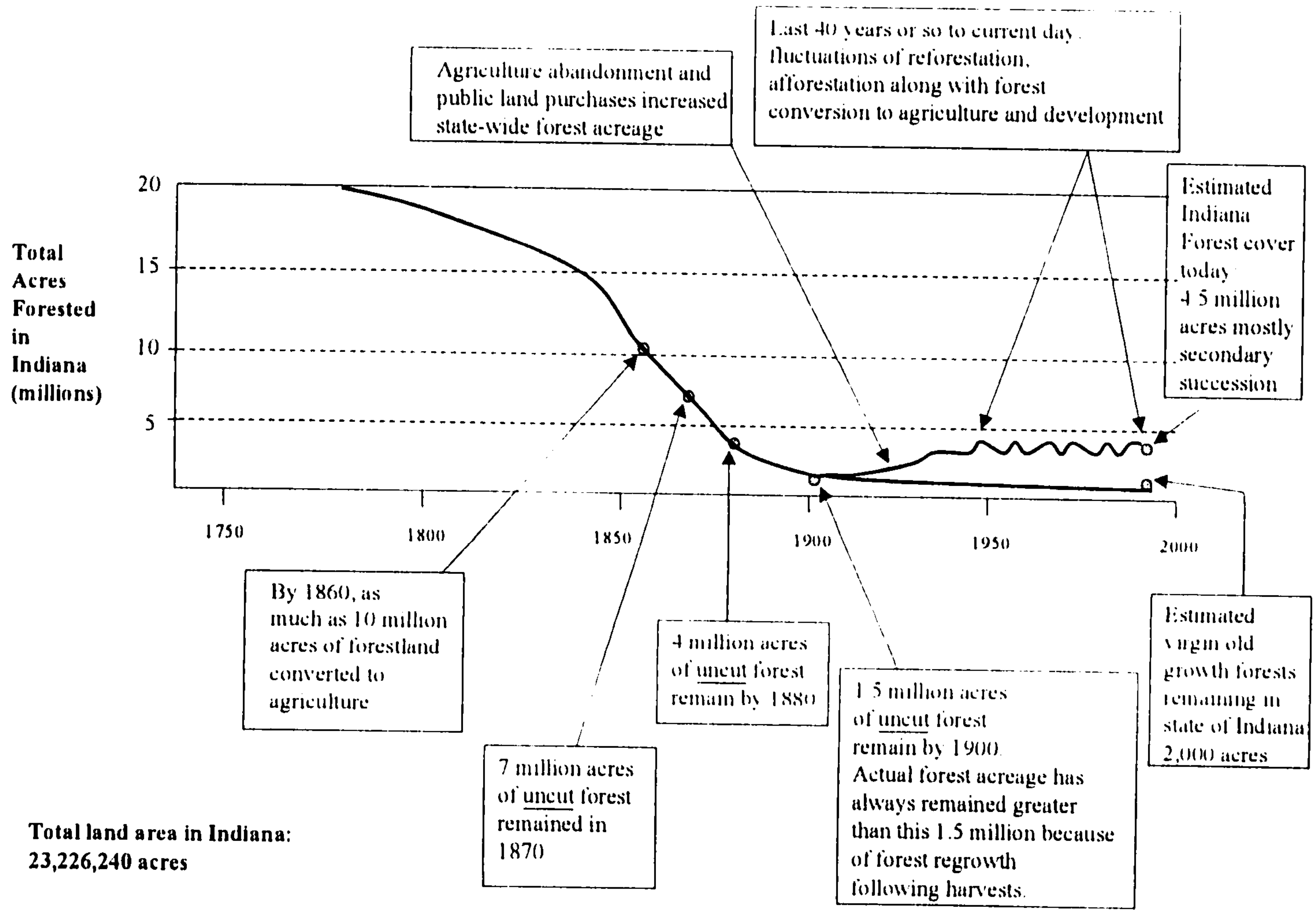


Figure 3-2: The Five-County Study Region and the Two Footprints of Landsat

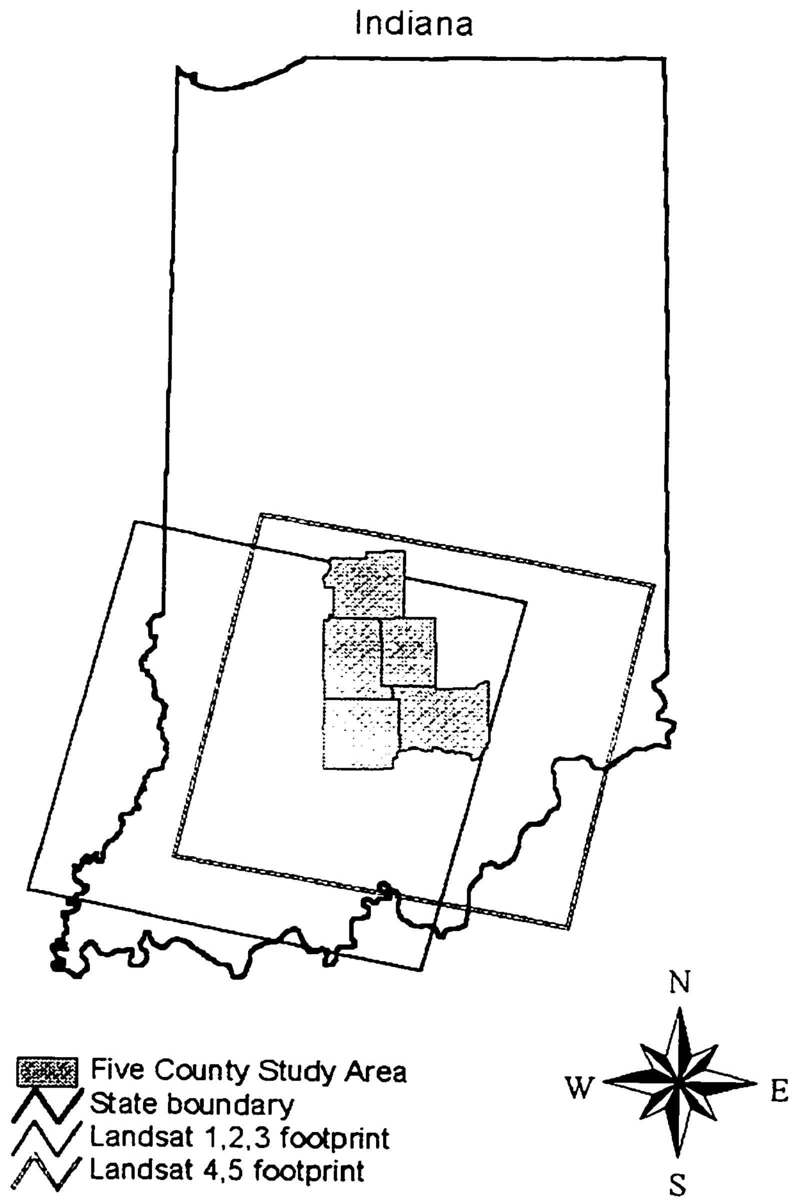


Table 3-1. Dominant Forest Vegetation Categories, Associated Species and Typical Locations for Growth in Brown County Hill Area
(Adapted from Barrett, 1980; and Homoya and Huffman, 1997)

Forest Classification Type	Typical Species	Typical Location
Oak-Hickory	White, Red, Black, Post, Chestnut Oaks, Hickories (e.g., Shagbark)	Ranges from deep, loamy productive soils to dry, shallow-soil ridgetops. Also on sunny, south-facing slopes. Xeric forests.
Elm-Ash-Cottonwood	American Elm, Green Ash, Eastern Cottonwood, Silver Maple, Hackberry, American Sycamore, Black Willow, Boxelder, Black Walnut	Found principally in bottomlands and flood plains bordering rivers and streams.
Beech-Maple or Mixed Hardwoods	Beech, Maple, Yellow Poplar	Often found in lower slopes and coves in unglaciated land. Found also on sheltered north-facing slopes. Mesic forests.

Chapter 4

INCENTIVE STRUCTURES, DECISION-MAKING AND DIRECT ACTIVITIES IN INDIANA'S PUBLIC FORESTS: GENERATING TESTABLE HYPOTHESES

Recall from Chapter 1 that change in the physical landscape is a response to either natural nonanthropogenic actions or patterns of human activities. Anthropogenic induced forest disturbance is a result of humans making choices under particular incentive structures and taking corresponding actions. Each individual operating within a forested environment faces a decision about the actions to undertake. Incentive structures that characterize the location at a particular moment in time drive what activity to undertake and where it should be conducted. The particular three-dimensional configuration of physical and institutional landscapes defines the incentive structure (Chapter 1, Figure 1-1)

The focus of this second part of the dissertation–and the dissertation as a whole–is to reveal how incentives can be related to actions and how actions can be related to outcomes in forested landscapes. I would ultimately like to be able to investigate incentive structures and outcomes across all types of property regimes: Public, private, nonprofit and communal, but this is too large a task for a single dissertation.[1] It is logical, then, to begin with a study of property management that has a relatively well documented history related to the three landscapes. Thus, this second part of the dissertation examines incentive structures, activities and outcomes in publically owned and managed forests in Indiana. It compares the incentive structures facing one group of state forest property managers with the incentive structures faced by one group of national forest property managers.

Prior comparative research (e.g., Koontz, 1997) reveals differences between the incentive structures driving the work strategies of these two types of public property managers. If state and national forest incentive structures are different, the prioritization of activities they undertake is likely to be different. If their choices of in-the-field activities are different, then the conditions of the forests they manage are likely to exhibit change that can be related to these different activities. An empirical question, one that will be taken on in subsequent chapters, is whether these physical changes are apparent in a time series of multispectral satellite images.

The goal of this chapter is to develop testable hypotheses that relate incentive structures of state and national foresters to predicted activities and ultimately to outcomes in forest change. To achieve this goal, this chapter follows this logic. First, I describe more clearly who are the actors in public forest management and what activities they typically choose among. Second, I explain the approach taken to analyze these actors' incentive structures and present the assumptions made related to their decision-making process in choosing operational-level activities. Third and fourth, I summarize the property manager's incentive structure history for the two public forests I intend to compare: Indiana's Hoosier National Forest and Yellowwood State Forest. The chapter concludes with testable hypotheses relating incentives to predicted activities for each of these two forests. I will test these hypotheses in subsequent chapters.

Actors and Activities in Public Forests

Chapter 1 presented three categories of "resource stewards" who make decisions and take actions within forests. Applying this list to public forest management settings, the first category, "high-level decision-makers," includes actors who develop and institute policy related to the management of forest resources. They rarely undertake direct activities on the resource itself, but they often establish laws, regulations, or standard operating procedures—portions of a forest property's institutional landscape—that other actors working within the forest boundaries are obliged to consider before undertaking particular activities. We could refer to the second category of actor in a public setting generally as "property managers." These are agents of a government who are delegated responsibility for the daily operation and management of a forest property. This would include the designated manager of a public forest property and his or her staff (e.g., professional foresters, "resource specialists," and researchers). We could refer to the third category in a public sector setting as "the general public," and include all those interested in using forest resources and have an interest in the way public forests are managed. These can be direct users of the forest (e.g., hikers, hunters) or other interested parties (e.g., environmental protection groups both locally or nationally). I consider timber companies who bid for the rights to extract timber part of this third group.

The activities humans undertake in forests can be thought of in terms of their impact on a forest landscape, that is, in terms of vegetation disturbance. Recall from the brief discussion in Chapter 3 that one approach to analyzing human activities is to organize them by preferences, interests and values. I follow Koontz (1997), and organize them by preservation, recreation and commodity interests. Such an organization is useful as we move toward hypotheses related to direct activities and resultant changes in at-satellite reflectance.

Preservation and Protection Related Activities

Table 4-1 lists forest "preservation and protection" related activities. Often in public forest settings, the institutional landscape may be subdivided such that portions of the physical forested area are designated protected. In these circumstances no human-induced forest disturbance activities are permitted.

Preservation and protection activities can occur at many different spatial scales. In Table 4-1, they are organized into three subcategories: large scale (protected areas 10 acres or greater), medium scale (protected areas between one and 10 acres) and small scale (less than one acre).[2] Obviously, large scale protection efforts will be easier to identify than small scale ones in satellite images.[3] Nevertheless, if a sample of these areas are identified, it should be possible to develop a library of "change spectra" from a time series of satellite images that provide a reference for vegetation that is not subject to human interference.

*** Table 4-1 about here ***

Recreation Related Activities

Popular recreation related activities in south-central Indiana are typical of ones conducted elsewhere in the United States. Table 4-2 categorizes recreation into two subclasses: preparation\maintenance and actual recreation.

*** Table 4-2 about here ***

The "preparation\maintenance action" category bundles together activities related to the alteration of the forested landscape in preparation for recreation. Public property managers, for example, are often involved in repairing damaged hiking trails or camping facilities before the spring and summer months when recreational hikers and campers are more apt to visit the resource. These types of efforts are commonplace and may take up a significant amount of time for property managers and other actors, but in all but very major initiatives the disturbance to forested canopies will be small. Most actions of this type occur beneath the canopy making it unlikely that they will be identified in later summer MSS images.

"Recreation actions" categorize all uses humans have for forest resources that are purely for enjoyment purposes. Recreation in Indiana typically involves one or more of the following activities: horseback or motorized vehicle riding, mountain biking, hiking, hunting, camping, visual aesthetic enjoyment from a location within or beyond forest property boundaries, and even for some religious practices. Most of these activities, individually, will not disturb a forest enough to produce change in forest condition that would be witnessed on a satellite image. However, sometimes, where the operational-level rules related to these activities have remained constant for a long period of time, some real, geographically significant forest disturbance might be made. For example, soil exposure resulting from continuous horseback riding, motored vehicle riding, and mountain-biking might be identified on satellite imagery, depending on the size of the trails, the canopy structure surrounding the trail and the terrain of the forest.[4]

Obviously, other recreational activities such as the use of a forest landscape for esthetic enjoyment or religious practices would not be identified in satellite imagery in terms of some dramatic imprint. However, the institutional landscape may be organized in a way that protects highly visual areas from cutting. In many Indiana state forest properties, areas near roads are often designated as "visual enhancement areas" and are subject to special considerations related to timber cutting and other activities (Allen, 1997). These areas could exhibit similar spectral qualities to other areas designated as protected.

Commodity Related Activities

Commodity interest related activities are listed in Table 4-3. I have defined them as activities taken by actors or groups of actors who wish to secure some economic benefit from a physical resource contained within the forested landscape. One way of organizing them further is to divide them into development or mining interests, and actions related to silviculture and forest management interests.

*** Table 4-3 about here ***

Development and Mining

"Development" activities may not be the first direct action one typically thinks of when considering forest related actions and satellite imagery but it is the action that may produce the most extreme change in light reflectance. Much of the south-central Indiana landscape, especially areas under private property, has been subject to this type of activity over the life span of satellite systems.

Like preservation and protection, I divide development into large, medium and small-scale categories. They each include similar types of direct actions, the difference between them is largely the geographic extent to which they are performed. Large-scale development captures the event where a significant geographic area of the forested landscape is dramatically converted into some other land use, such as a large housing development, recreational area development (such as a golf course), conversion of forest to agriculture land or pasture. A development activity of this degree would be readily apparent on MSS satellite images and, at least with respect to home and commercial development, would exhibit a reflectance pattern moving from forest vegetation to some permanent level with soil type properties. Medium-level development activities include similar sets of actions as large-scale (e.g., housing\commercial development, agriculture conversion) plus some others (e.g., road or utility line construction) and occur in smaller geographic areas (between one and ten acres). Small-scale development is defined here as activities that disturb one acre or less of the landscape and will most probably be the most prevalent development activity witnessed over time. Small-scale development activities comprise very similar activities as the other two categories plus a few others.

"Mining" interests can be categorized in a similar fashion for there may be areas where large-, medium- and small-scale mining is undertaken. Indiana has a long history of mining for products such as limestone, and there is the chance that some forested areas may have been disturbed by these activities. Since mining interests are similar to other development interests, they are classified together in Table 4-3.

In some rare instances, direct actions related to forests could be an indirect by-product or externality of other human activity. For example, there have been incidences where forest vegetation reflectance as witnessed on satellite imagery has been altered as a result of vegetation response to industrial waste in the air (Green, personal conversation, 1997). Acid rain provides another example that occurs at a broader geographic scale (Hedin and Likens, 1996). While these types of incidents may be rare in south-central Indiana, they could occur and thus should be recognized.

Silviculture and Forest Management

Silviculture, as defined by Robinson (1988: 61) is the "art and science of growing trees." There are a wide variety of activity categories that fall under this label including: stand area preparation, regeneration, stand tending and protection, intermediate thinnings, and even-aged or uneven-aged harvesting.

Stand area preparation is a direct activity often conducted after a forest stand has been harvested or after some type of natural disturbance (e.g., tornado) has occurred (Kimmins, 1992). Residual debris from this disturbance, may not leave the area in a condition that is ideally suited for the regeneration of a desired type of species. Logging slash or downed tree stems may have created a microecosytem that is not deemed appropriate for the type of vegetation the property manager thinks is needed. Site area preparation then involves several types of techniques to create a more favorable growing environment: salvage harvesting, slashburning, mechanical and chemical treatments. Salvage harvesting describes operations taken to remove valuable trees damaged by a natural phenomenon such as a tornado or windthrow. Slashburning involves the burning of residual debris left from a disturbance. Mechanical treatments involve the physical movement of slash debris to create locations more conducive for trees to regenerate naturally or though planting. Chemical treatments have been used in some cases to reduce competition from weeds and tree species deemed unfavorable by the direct action decision-makers (Merritt, 1980). Stand area preparation activities may or may not produce results that are directly visible on satellite imagery depending on the size of the geographic area treated.[5]

There are several different general types of regeneration activities. One very simple method is the reliance of natural successionary processes. In many property regime settings, an investment in the landscape is made by just letting the natural growth processes occur without any human intervention. Work conducted by Moran and colleagues (e.g., 1994a, 1994b, 1994c) has begun to capitalize on the different spectral qualities of forest successionary stages.

Planting is a second regeneration activity and has three attributes that are different from natural successionary processes (Kimmins, 1992). These may be important determinants in what we see in some areas of satellite imagery. First, the seeds or seedlings utilized in planting initiatives may differ genetically from the vegetation that existed in the geographic area previously. Second, planting often produces a homogeneous (in age and species) stand.[6] Third, the spatial distribution of the stand can be better controlled. A plantation may have a very consistent, systematic spectral quality to it as a result of systematic planting.

"Stand tending" refers to the types of activities conducted to reduce the likelihood of a stand being subject to damage by insects, animals or other vegetation (Kimmins, 1992). Natural repellants developed from glands of large predator animals, for example, have been used to deter deer and other animals from grazing in a particular area (Ibid.).

"Sanitation" cuttings are sometimes used to minimize the spread of insect infestation or disease (Smith, 1962). Like stand area preparation, these types of practices may be conducted in areas of small spatial extent and may or may not be apparent given the resolution quality of satellite imagery There may be other instances where areas large enough to impact the at-satellite reflectance at the pixel[7] level on an image have been subject to stand improvement activities.

"Intermediate thinning" of trees is often conducted in immature stands to enhance the growth of other trees or to increase the total yield of useful material (Smith, 1962; Kimmins, 1992). The goal of thinning traditionally is to distribute further growing space to trees that are considered favorable and also to utilize the timber of other trees that are unlikely to survive in lieu of other competition.[8]

Forest management, in timber production terms, entails either even or uneven-aged strategies. The even-aged method attempts to harvest a particular forest stand in such a way that most or all of the trees within that stand remain generally of the same age class (Kimmins, 1992). Stands managed under even-aged methods typically range from 15-20 acres to 300 acres (Robinson, 1988). In an even-aged stand, three dominant types of silvicultural systems are typically used: clearcutting, seed tree, shelterwood and strip or patch cutting (see Figure 4-1; Ibid.; Kimmins, 1992). Clearcutting systems remove all of the timber from the area at the same time. From a disturbance point of view, it is the most dramatic of all cutting methods. Seed tree systems also clearcut. However, carefully selected healthy trees are left remaining in strategic locations to provide seeds to support natural regeneration processes. Shelterwood systems involve heavy cutting as well, only the harvesting is conducted in several stages. By conducting harvesting in stages—what are sometimes referred to as "regeneration cuts" (Kimmins, 1992)—seedling products from remaining trees have time to be established in these modified environments. Strip and patch cutting involves selecting various areas within a stand area to be harvested at a particular time (Smith, 1962). The most straightforward approach to this is to undertake strip cuts at short, regular intervals throughout the stand with the entire stand being harvested within a period of 10 to 20 years depending on the rotation length. Patch cutting is a similar technique that involves the clearcutting of smaller patch areas within the stand. During the 1970s and 80s, clearcutting was the silviculture method of choice for the Forest Service across the U.S. and in the Hoosier National Forest.

Uneven-aged silviculture methods utilize any of the four even-aged methods over smaller geographic areas or may apply two other techniques: group and single tree selection (Robinson, 1988). These two selection methods involve the identification of individual trees to be cut, usually above a particular diameter limit. Other damaged, suppressed, insect-infested or diseased trees may also be removed. Group selection tends to be the more popular of the two selection methods, because in practice it is easier to conduct than individual tree selection. Regardless of which method is applied, the goal is the same: produce smaller gaps in the forest stand to create a stand that always has an uneven-aged and reasonably dense look to it at all times. It is these last two uneven-aged methods that appear to be the dominant sivilculture techniques used over the past twenty years in the state forests studied in Indiana.

Regardless of strategy, a result of harvesting activities that may become apparent in satellite imagery is increased soil exposure caused by the use of truck and skidder access roads. Additionally, there may be information in the reflectance of even and uneven-aged canopies that allow us to identify general spectral consistencies produced by the harvesting method in certain topographic environments. For example, even-age stands may exhibit a more homogeneous spectral pattern and less canopy-produced shadow. It is likely that the outcome of uneven-aged silviculture activities will be less apparent on satellite imagery than even-aged practices because the latter are conducted over larger geographic areas. They therefore are more likely to produce more spectrally significant differences between before and after satellite images. Uneven-aged stands, on the other hand, could produce a more heterogeneous reflectance (than comparable even-aged stands) and exhibit a larger amount of canopy-produced shadow. Regardless of the method used, the likelihood that any silviculture practice will appear on a longitudinal set of satellite imagery at any given location is linked critically to the rotation period and the size of the stand treated. Empirical questions related to this issue–the sensitivity of satellite images to silviculture treatments used in Indiana deciduous forests–are investigated in the Chapters 5 and 6.

Analyzing Incentive Structures and Human Decisions Related to Activity Choices

With the general types of activities defined, let us now move onto a discussion of how humans choose which activities to undertake. Earlier, three categories of public forest actors were outlined: "high-level decision-makers," "property managers," and the "general public." The primary focus of this study is the decisions and activities undertaken by the second group—forest "property managers." This is because, to a large degree, they make the decisions related to where and when activities occur in a public forest. While there are instances where private citizens violate forest rules and policies and undertake illegal forest disturbance activities,[9] these are somewhat rare in the Indiana context. When they do occur, they will not usually affect a significant geographic region, but rather tend to occur in smaller forest property areas usually along property borders.[10] Therefore, most of the disturbance in forests captured by satellite images will be a result of activities undertaken or authorized by the property manager overseeing operations in the state or national forest.

If we intend to link forest property manager incentives to activities and activities to outcomes, it is important to consider the factors that influence the decision-making logic of these property managers. This section of the chapter provides a theoretically-based framework for analyzing the incentive structures that these property managers face in their day to day activities.

Assumptions About Human Decision-Making

If we are to analyze the incentive structures guiding property manager behavior, we must first consider the decision-making apparatus these actors apply in deciding appropriate direct actions to take on a resource. For this, I turn to literature produced in the fields of political science and economics labeled the "New Insititutionalism."[11] I find this literature particularly useful for it focuses attention on the individual actor and provide some initial assumptions about his or her decision-making and behavior. New Institutionalists assume that individual actors have relatively well defined preferences or goals, and assume that they have the capacity to assess, to at least some degree, the impact of alternative courses of action or strategies. They assume further that actors possess some capacity to assess the benefits versus the costs of a particular action: they can, with varying levels of success, choose one or more activities that they believe will lead to their most preferred result (Eggertsson, 1990: 12).

The assumptions above have followed closely with the assumptions of the rational actor in neoclassic economics. New Institutionalists, however, disregard the neoclassic economic assumption of full information and replace it with the assumption of incomplete information. Actors are assumed to possess gaps in their information related to choices between several alternative actions (Eggertsson, 1990; Firmin-Sellers, 1994) and therefore make the best decision they can given this limited information. The New Institutionalism assumes further that new or added information is often costly to acquire and that costs are incurred in the course of making transactions in economic exchange agreements (Eggertsson, 1990; Firmin-Sellers, 1997).

The Decision-Making Process in Public Forest Property Regimes

We tread on a shaky foundation when we begin to try and describe human decision-making for so much is still not well understood. Karl Popper (1967) suggests that instead of trying to focus heavily on the internal processing of human decision-making, it perhaps is better to treat it as largely a black box. To Popper, the analytic emphasis should turn more toward the development of fully specified models that include important observable variables that influence human decision-making. In her book *Governing the Commons*, E. Ostrom (1990: 33-38, 192-214) provides a broad depiction of the decision-making apparatus of a human actor making a choice between rule configurations. This depiction is her attempt to carefully balance Popper's black-box advice with an attempt to systematically understand the variables that were influential in determining the decision outcome. While her model of human decision-making depicts an actor making decisions regarding operational-level rules (collective-choice decisions), her model can be just as easily applied to an actor making choices between operational-level activities. This section builds on Ostrom's efforts and applies a similar analysis with an emphasis on the property manager's choice between a suite of possible operational-level direct activities. It is this level of decision-making–driven by the configurations of the physical, community and institutional landscape–that produce human actions that result in changes in light reflectance in satellite images.

The assumptions related to the largely "black box" internal decision-making processing of the individual forest property manager working at the operational level are presented in Figure 4-2. The diagram places a forest manager in the decision-making context she faces daily: that of determining what activities to undertake for particular forest locations. The question is: at any given time, what factors determine a chosen activity and the time and location in which it is undertaken? Building on Ostrom's (1990, 1997) approach, four "internal variables" play an important role in determining the choice of activity a property manager might take: expected benefits (Figure 4-2 A), expected costs (Figure 4-2 B), internal norms (Figure 4-2 C) and discount rates (Figure 4-2 D).

In considering the days activities, forest property managers are assumed to face a choice of many possible sets of potential activities (Tables 4-1 through 4-3). It is further assumed that, to some degree or another, these individuals weigh the expected costs and benefits of each activity–or at least of those with high priority. The activity she selects will depend largely on her information regarding benefits and costs of each activity choice, and how each activity choice fits in with her (and the accompanying community's) realm of acceptable behavioral norms.

For example, to the public property manager, it may be economically tempting to consider harvesting a stand of mature hardwoods residing along a border of this property. The decision of whether to undertake this activity will be based on a weighing of the expected benefits (Figure 4-2 A) of the cut (e.g., the potential financial return in today's dollars of the timber, possibly also freeing up of the land for other land uses such as development), versus the expected costs (Figure 4-2 B) (e.g., logging roads required, the potential damage to the land and whether the action is in conformance to existing operational rules, potential protests made by nearby landowners or environmental groups).[12] Further, considerations about adjacent neighbors' feelings and their expected reaction to cutting initiatives may raise the expected costs of the action. Similarly, the internal norms (Figure 4-2 C) of a particular actor, regardless of community norms, may influence the benefit/cost calculus of a particular direct action. A manager with particularly strong protection values related to specific trees would likely judge the cost of a cut to be higher than would a property manager less concerned about the protection of such trees.

Property managers are assumed to discount the value of future benefits they expect to receive from particular actions (Figure 4-2 D). The severity of the discounting depends on the time horizons and in particular the economic conditions of the actor or actors involved. For example, one state property may be subject to a financial situation where little funding is available for a particular initiative. Depending on the institutional configuration related to how revenue is distributed after a timber sale (e.g., some of the profits remain in the property manager's budget), the forest manager may apply a high discount rate in his or her internal calculations If additional monies are needed and sale profits are allocated back to the state forest property, she may decide to capitalize on the current economic value of a stand of trees and authorize a timber cut on that stand. In this situation, the property manager may feel the economic benefits today outweigh the costs of an early successionary forest in future years. Alternatively, another public forest manager facing a budget surplus year may arrive at quite different conclusions. A low discount rate is applied: the economic opportunities forgone by not cutting today are deemed less important than the investment returns that will be received in future years.

Figure 4-2 also captures the assumption that property managers utilize information to inform their decisions. Three types of information are utilized: (1) the costs of a proposed activity (Figure 4-2 E); (2) the benefits of a proposed activity (Figure 4-2 F); and (3) shared norms and other opportunities (Figure 4-2 G) In many instances, a significant amount of this information is derived by the property manager himself or herself using his or her knowledge and understanding of the forest property's physical, community and institutional landscapes (Chapter 1, Figure 1).

Information about Costs of a Proposed Activity (Figure 4-2 E)

As Tables 4-1 through 4-3 reveal, there are a significant number of activities a forest manager can choose to undertake. However, depending on the particular setting–the configuration of physical, community and institutional landscapes–the cost of a particular activity may be recognized as too high and may result in the activity excluded from serious consideration.

For example, information a property manager possesses about the physical landscape of the forest or a particular tract[13] may make the cost of undertaking the activity exceedingly high. Certain activities, such as any of the suite of timber cutting methods in Table 4-3, may not be an option in physical settings where the action is infeasible (e.g., extremely steep slopes, glades, cliffs, and swamps). Alternatively, flat and easily accessible areas may be given higher priority for these types of activities. The influence of topography is thought to play an important role in determining where forested land exists in Indiana (Sieber and Munson, 1992; McCracken, Safar and Green, 1997).

Information about the community landscape also affects the costs a property manager expects to incur if a particular activity is undertaken in a tract. For example, public forest tracts that are immediately adjacent to private property parcels have a higher likelihood of creating unrest in the neighboring community and complaints if a timber sale is conducted.[14] Alternatively, a timber cut conducted on a tract completely surrounded by other public land and visually protected in some way by the physical environment may receive fewer complaints from citizens. In Indiana, certain state forests appear to receive more interest from citizens than others, which has been attributed to a component of their community landscape–the characteristics of the human community in nearby towns and cities. For example, Yellowwood State Forest receives considerably more public attention than other state forests (Fischer, 1997) and in part, this is attributed to its geographic proximity to Bloomington–a city with a high degree of conservationalist values and recreation interests. The costs of conducting a controversial forest management activity may be deemed higher in situations where there is an interested and motivated neighboring community.

The information a public property manager possesses concerning the configuration of the institutional landscape also contributes to his or her anticipated cost of undertaking a particular activity. Koontz (1997) identifies several components that may affect the costs or benefits of particular activities (discussed more below). While he does not specifically articulate these as the "fabric" of institutional landscapes with their own 2- or 3-dimensional properties, they can be thought of in this manner. These components include: legislation, executive orders, organizational planning documents, standard operating procedures (SOP) and revenue rules and allocations.[15]

In "landscape terms," some of these components, such as legislation or executive orders, can be thought of as institutional "layers" that "blanket" the entire public forest property. For example, a law, executive order or SOP might prohibit a particular activity from being undertaken anywhere within the forest property. Alternatively, other laws, executive orders or SOPs may specify only certain geographic locations where particular actions are prohibited (Schweik, 1997). For example, it is typical in public settings to have special management rules placed on riparian areas. A property manager who is considering an activity that is prohibited or discouraged is likely to add the additional cost of a negative job performance review in his or her decision calculus (Koontz, 1997).

Revenue rules and allocations also have a geographic component to them. They, like legislation, executive orders or SOPs might be allocated to the entire property as a whole. Revenue may be appropriated to an "operating fund" that can support a variety of activities with no specification on where within forest property these activities must take place. In other instances, appropriated money may be authorized for a specific purpose or location within the property boundaries. If a property manager considers using monies to pay for an action that is not for the intended purpose, his or her expected costs to undertake that action, again quantified in terms of a negative job performance review, rises. But probably the most common budgetary problem facing public managers is having too much to do and not enough financial resources to support every desired activity. Under these circumstances, property managers prioritize and simply drop or postpone activities from consideration if they are too expensive.[16]

Information about the Benefits of a Proposed Activity (Figure 4-2 F)

In a similar fashion, information about the three landscapes is utilized by a property manager to calculate the expected benefits of an activity. The physical landscape configuration, of course, plays a significant role in this calculus. For example, stand tending, or thinning (Table 4-3) activities are undertaken to control vegetation deemed undesirable and to boost growth of preferred trees. Similarly, the physical attributes of certain forested areas may be considered important wildlife habitat locations that require human activities to maintain or improve them.[17]

The community landscape, through demands for certain forest uses, plays a role in influencing the benefits a forest property manager might place on a particular activity. For instance, the property may face significant demand from the neighboring human population for recreational uses of the forest (e.g., improved hiking facilities). The anticipated "positive response" of forest visitors to new or improved recreation facilities may add to the expected benefits a forest manager perceives related to this activity. Similarly, if there is added pressure from state or local governments or other interested parties (e.g., timber companies) to undertake certain activities, the forest property manager might weigh these activities higher.

And again, the institutional landscape is an important information source for the property manager. I consider new scientific information related to a particular type of silviculture method to be one component of the institutional landscape that may manifest itself in updates to an organization's standard operating procedures.[18] If the activity is high up the organization's priority list as defined by a mission statement or operational plan, a larger expected benefit will be associated with that activity. This also touches on the mechanisms in place for employee evaluations and incentives. If particular legislation, regulations or revenue procedures encourage timber sales to improve budgetary situations, a forest manager will likely place a higher expected benefit on timber cutting activities. If budgetary allocations are designed in such a way that all or portions of the profit of an activity are returned to the local forest manager's organization, even more benefits may be associated with that activity.

Information about Shared Norms and Other Opportunities (Figure 4-2 G)

The method in which a particular property manager weighs her expected costs and benefits depend on internal norms and her internal method of discounting the future (Ostrom, 1990:205). Ostrom builds from the work by Coleman (1987) who distinguishes between internal and shared norms. "Values" is another term often associated with this concept (Cramer, *et al.*, 1993; Koontz, 1997). It is assumed that the property manager holds some degree of internalized norms regarding appropriate activities to undertake in certain landscape configurations. The guilt and\or anxiety a property manager may experience about an activity he or she feels is incorrect for the particular tract will increase the expected costs he or she relates to that activity as it is considered (Ostrom, 1990). Conversely, a property manager may feel a sense of pride or achievement when considering other activities she considers particularly beneficial to the property. This adds to the expected benefits she associates with these "pride" activities.

Information on shared norms also plays a role in the decision-making calculus (Colman, 1987; Ostrom, 1990). The norms established in an organization, sometimes referred to as "culture" (see for example, Schein, 1985), are thought to influence the behavior and decision-making of participants within that organization. Foresters acting together, day in and day out, are apt to develop norms of acceptable and unacceptable behavior and will convey these expectations in various action settings (Ostrom, 1990).

Information on other economic opportunities also may influence the discount rates the forest manager applies to a certain activity (Ibid: 206). For example, one stand might be left untouched in a given year because there are other tracts within the property whose trees are more mature and profitable for a timber cutting activity. The economic gain that these older stands bring results in a discount rate that is lower for less mature tracts. In other circumstances, a budget surplus might decrease the discount rate associated with a particular planned timber harvest activity. Further, changes in the institutional landscape such as a modification to the organization's mission or goals might also affect the discount rate applied to the expected cost and benefit calculus for a particular activity.

In summary, the information available on the costs and benefits of an action, along with information on other economic opportunities and organizational and community norms affect the way expected benefits and costs are perceived. It is assumed that monthly, weekly, or even daily, the property manager takes the available information, applies it in his or her internal calculus and "satisfices" to arrive at an appropriate operational-level strategy for the property he or she manages.

Applying this Discussion to the Study of Change in Public Forests

Physical, community and institutional landscapes change over time. How and why physical landscapes change is at the heart of this research. Understanding community landscape change requires an analysis of demographics and migration patterns. In south-central Indiana, population growth, decline and migration patterns have played a major role in the long term change in the forested landscape (McCracken, Safar and Green, 1997). Clearly, community landscape change has occurred in the south-central Indiana landscape during the 1972-1992 period. Understanding how, however, requires more effort than can be allotted here. Similarly, understanding institutional landscape change requires analyses of collective-choice mechanisms–rules and procedures for establishing and maintaining operational-level rules. This too, requires a more detailed analysis that is beyond what can be accomplished in this study.

But to understand how *incentives influence activities* and *activities influence physical outcomes* it is not necessary to understand *why* institutional landscapes have changed over the study period. Instead it is vital that we understand *how* the institutional landscapes were configured–both substantively and geographically–over time.

The rest of this chapter, then, turns to this endeavor. It begins the comparative part of this study, examining the incentive structures for property managers in two public forest settings only a few miles from one another: Hoosier National Forest Pleasant Run Unit and Yellowwood State Forest (Figure 4-3). There are several reasons why these two forests were selected for comparison. First, while they certainly have distinguishing characteristics in terms of their physical landscapes, to a large extent (e.g., vegetation types, proportions of slope and elevation classes) they are very similar. They both are very close in proximity and both fall in Homoya's (1997) "Brown County Hills" area of Indiana. Second, while the community landscape in south-central Indiana has surely changed over the 1972-1992 period, given the close proximity of the two forests to one another it is a safe assumption that the community interested in using these both these forests have been largely the same. Moreover, Koontz (1997) found few systematic differences between state and federal property managers in terms of their beliefs and values. The community landscapes can be assumed then to have remained largely similar across time.

But what is likely to have differed significantly between the two forests is their past and present institutional landscape configurations. These institutional differences are expected to greatly influence the cost and benefit calculus of their individual property managers. It is hypothesized that the differences in the institutional landscapes over time will be a major factor in determining how the landscape has changed over time in these two forests. A comparison of these two forests provides an opportunity to investigate how institutions affect incentive structures, how incentive structures affect property manager actions, and how actions affect outcomes as they are captured by multispectral satellite images, all the while keeping the physical and community landscapes largely constant.[19]

The next two sections describe each of these two forests with an emphasis on the history of their institutional landscape. The final section of this chapter presents hypotheses on expected activities based on an understanding of their incentive structures over the 1972-1992 period which will be tested in subsequent chapters.

A History of the Institutional Landscape and the Incentive Structures of Hoosier National Forest Property Managers: 1972-1992

A Brief History of the Hoosier National Forest

The Hoosier National Forest's origin began in 1911 when the U.S. Congress under the Week's Act authorized funding to purchase lands to establish national forests (Sieber and Munson, 1992). At about this same time, eighteen states in southern Indiana counties were losing significant amounts of topsoil. A survey conducted by Aldo Leopold in 1931 estimated that an aggregate of 405,000 acres of farmland was lost to erosion and soil degradation between 1910 and 1925 (Doemel, 1980).[20] Figure 4-4 displays a map created in 1935 from data collected by the USDA's Soil Conservation Service. It delineates areas within the state by their percent of sheet erosion and gullying. By this year, the Forest Service had received many offers from land owners wishing to sell a cumulative 200,000 acres of private property. These farmers were hit simultaneously by the economic troubles during the Great Depression and also the physical problems of erosion on marginal agriculture land. Alarmed by the condition of the idle lands and the delinquency of tax payers in the region, in 1935 the Indiana General Assembly designated the hills in southern Indiana's as national forest area (Outdoor Indiana, 1935a). The Hoosier National Forest was officially dedicated in 1951 with two primary goals: conservation of natural resources and assistance to the economy of southern Indiana by providing recreation areas (Ibid.; Doemel, 1980).[21] Hoosier National Forest's boundaries, shown partially in Figure 4-3, [22] cover an estimated 644,291 acres (Doemel, 1980: 5) but have never been completely owned and managed from the U.S. Forest Service. Within the borders is a matrix of public and privately held land. The Forest Service continues to purchase land within these boundaries when a seller is willing (USDA Forest Service, 1991a). Note how the locations of today's Hoosier National Forest (and Yellowwood State Forest) shown in Figure 4-3 follow closely with the high soil erosion areas designated in Figure 4-4.

During the Great Depression, the federal government also assisted in economic recovery through the mobilization of the Civilian Conservation Corps (CCC). This program hired out of work people to undertake initiatives managed by the U.S. Forest Service and the Indiana Department of Conservation. This is important for this study, in that these workers spent much of their time replanting barren areas in the new national forest and also in state forests (Sieber and Munson, 1992). Scattered throughout the physical landscape of these areas are non-natural remnants of this activity—approximately 32,000 acres of pine plantations (USDA Forest Service, no date) –which are readily apparent in multispectral satellite images even today. White, Jack and Virginia pine were seen as the only species that would produce satisfactory forest growth in poor soils (Wilcox and Shaw, 1935:16).[23]

The Hoosier Pleasant Run Unit Institutional Landscape in the 1960s, 1970s and early 1980s

The institutional landscape of the Hoosier National forest has changed over the years and for this study, we are particularly interested in its composition and change over the 1972-1992 period because this is the time frame that matches the available time series of satellite images. For this study, I focus on the components of the institutional landscape that comprise operational and collective-choice rules.[24] Each and every rule, regardless of level, has a geographic property associated with it. It either (1) blankets the *entire* property as a whole or (2) blankets specific subareas within the property boundaries. Building from Koontz (1997), there are several institutional categories that may specify either collective-choice or operational-level rules: legislation and agency regulations, revenue rules and allocations, and organizational planning documents and standard operating procedures (SOPs).

Legislation and Agency Regulations

Many of the earliest federal forest-related legislation mandated particular types of operational-level activities. Legislation and regulations governing the "wise use" of public forests were put in place shortly after the first national forest properties were created in 1891. The Organic Act of 1897,[25] for example, authorized the selling of timber on these lands and began a debate on appropriate management activities–a debate that still continues over a century later. The history of the Forest Service and its management practices is beyond the scope of this dissertation, however, it is important to mention some critical legislation[26] that governed the Hoosier National Forest property in the years just prior to the acquisition of the first image in this study (September 30th, 1972).

The Multiple-Use, Sustained-Yield Act (MUSYA) of 1960 specified approaches to operational-level management in National Forests. This Act directed the Forest Service to manage their properties for six major uses: timber, wildlife, range, water, outdoor recreation and wilderness. The Forest Service's defined multiple-use management as management such that "no resource is emphasized to the exclusion or violation of the minimum standards for other resources" (USDA Forest Service, 1985: p. 2-12). While all six uses must be provided in a national forest setting, the MUSYA does not require every specific stand within a forest property to supply all uses. Some areas could be set aside for recreation, while others could be utilized for other forest products such as timber.[27] MUSYA also requires timber management to be conducted under the "principle of sustained yield"–that timber could only be extracted at a rate no higher than what the forest could sustain without depletion of the resource (Clary, 1986). "Multiple-use plans" were made by each National Forest District and these plans usually zoned national forest land (USDA Forest Service, 1985a). Unfortunately, if these zoning plans did exist for the Hoosier National Forest for the 1960s and early 70s, they could not be located.[28]

While on paper, the multiple-use directive gave the impression that at a national level the Forest Service nationally was shifting away from an emphasis on timber production. To many however, especially people in the Pacific Northwest, the multiple use mandate was a "meaningless slogan, hiding a devotion to timber production" (Clary, 1986: 187). It appears that even in Hoosier National Forest management it took many years for the multiple use planning philosophy to really take hold.

Other important national forest legislation–the Wilderness Act of 1964 (16 USC 1131-1136) and the Eastern Wilderness Act of 1975 (88 Stat. 2096)–followed MUSYA. These laws emphasized the "wilderness" component of the list of multiple uses for national forests east of the 100th meridian (Doemel, 1980). In the case of the Hoosier, it wasn't until December 12, 1982 that Congress officially designated the 12,953-acre Charles C. Deam Wilderness area. This wilderness designation appears to be one of the first broad geographic areas in Hoosier subject to a different set of operational-level rules.

In 1969, the enactment of the National Environmental Policy Act (NEPA) added a hurdle to the initiation of operational-level activities, requiring all federal agencies to prepare documentation describing the environmental impacts of any "major" activities that would "significantly" affect the natural environment (42 USC 4321-4335). NEPA altered the collective-choice environment, by requiring forest officials to undertake communication with interested citizens about the proposed action and providing them an opportunity to appeal both within the agency and also in the courts (Rosenbaum, 1985). The procedural requirements NEPA place on forest officials is significant. Interviews with national foresters within four different U.S. states performed by Koontz (1997: 81) reveals a frustration in the amount of effort it takes to prepare project documentation that is, in one forester's words, "appeal-proof."

The operational-level directives set fourth by MUSYA led to some problems in meeting sustained-yield requirements, particularly in the Pacific Northwest (see the discussion by O'Toole, 1988). The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) was an attempt to solve some of these problems by requiring the Forest Service to inventory all renewable resources, evaluate methods for improving the yield of goods and services provided by these resources, and provide a cost\benefit analysis on alternative methods to improve these yields (Doemel, 1980). RPA also requires a market assessment of current markets for goods and services (to be conducted every 10 years), and an evaluation of the forest program every five years.

Operational-level directives in RPA led to an increased concern by some citizens over a potential reduction in the national timber supply, but these concerns were countered by a growing environmental movement dissatisfied with the increased use of clearcutting by the Forest Service over the 1960s and 70s (O'Toole, 1988). This debate led Congress to enact the National Forest Management Act of 1976 (NFMA) which amended RPA by requiring officials at each forest property nationwide to create a "Land and Resource Management Plan" every ten years. In the Hoosier setting, work began on this plan shortly after NFMA was passed.

Clearly, legislation has contributed significantly in determining collective-choice procedures and operational-level activities in the Hoosier during the 1970s and early 1980s. Since much of the land area designated Hoosier National Forest property was old abandoned farmland, it can be assumed that many or most operational-level activities beginning in the 1930s and continuing through the 1960s were devoted to land rehabilitation. However, as the forest vegetation matured in the early 1970s, opportunities for timber production in the Hoosier increased. Indiana has been known as an area that supplies high quality hardwoods (Clark, 1987; IDNR Division of Forestry, 1987), and from the 1960s to mid-1980s, timber extraction became an important operational level activity in the Hoosier. In fact, at the national level, during the 60s and 70s, many, including some within the Forest Service itself, felt the emphasis on timber production outweighed other multiple use management activities (Clary, 1986: 187). The increased emphasis on timber extraction during this period appears to be, in part, a result of the incentives created by these laws and agency regulations. The multiple use mandate encouraged forest property managers to assist the timber industry and local economies while remaining within sustained yield levels (O'Toole, 1988). And the early 1970s witnessed a concern over a national housing shortage, which added pressure for the Forest

Service to keep maintain cutting levels (Clary, 1986).

Revenue Rules and Allocations

Incentives for timber harvesting also were created through revenue rules and allocations. The Knutson-Vandenberg (K-V) Act of 1930 (16 USC 576-576b) authorized the Forest Service to retain a share of timber sale receipts for reforestation activities. NFMA later added a revolving fund generated from timber salvage sale receipts to subsequent salvage sales and associated roads.[29] NFMA also expanded the use of Knutson-Vandenberg funds for precommercial thinning, wildlife habitat improvement and other activities.[30]

Niskanen (1971) argues that a bureaucrat's utility function is based on salary, office perquisites, public reputation, power, patronage, organizational output, ease in which changes can be made, and ease of management. All but the last two are positively related to the budget of the organization. Building on the work of Niskanen, O'Toole (1988) reported that Forest Service property managers during the 1980s acted as "budget-maximizers." He argued further that the revenue allocation rules established by K-V and NFMA created an incentive structure that encouraged property managers to emphasize timber sales that builds "activity funds."[31] This literature suggests that there were significant revenue allocation incentives established during the 1960s through the 1980s to encourage timber cutting in the Hoosier. Moreover, during this period, Congress and several presidential administrations appear to have been more willing to support programs that were revenue producing (Clary, 1986).

Planning Documents and Standard Operating Procedures

Few formal planning documents and standard operating procedures guiding operational-level activities were published during the 1960s, 70s and early 1980s. What did exist during this period probably resides in interoffice memorandums (Turney, 1998). However, bits and pieces of activity guidelines can be pieced together from public documentation produced during that period.

Clearcutting was "by far" the most common harvest method employed during this period (USDA Forest Service, no date: 2). In the Pleasant Run Unit, between one and three million board feet per year were removed (Ibid.). While it appears that there were no landscape level management areas specified during the 1960s and 70s, guidance did exist on appropriate cutting practices. Timber sales contracts specified terms related to how direct activities should proceed and what measures should be taken related to environmental protection (e.g., stream course protection, logging road construction) (USDA Forest Service, 1973).

Fortunately, the SOPs for other direct activities that occurred during the 1970s and early 80s are described under "Alternative 1" in the 1985 Hoosier Land Management Plan. This "status quo" alternative summarizes the level of goods and services that the Forest provided prior to the 1985 plan and also contains a map of the institutional landscape as it existed during this period. Figure 4-5 provides a map of Hoosier's Pleasant Run Unit. Within this unit boundary are "management areas," defined as areas with "common direction, with one management prescription applied to achieve the desired condition of the land" (USDA Forest Service, 1985b: 2-57).

Prior to 1985, the Pleasant Run Unit contained three main management areas (labeled "3.2," "5.1," and "7.1") (Figure 4-5). The majority of Pleasant Run was designated a "3.2" management area prescription, an area designated for multiple-use management, where efforts to preserve wildlife habitat are made, recreation is allowed, but timber cutting is emphasized and mining, oil and gas exploration is permitted.[32] A more detailed summary of the operational-level activities permitted in this and other management areas are shown in Table 4-4. The "5.1" management area encompasses the "Charles C. Deam Wilderness" designated in 1982. After 1982, the only permitted operational-level activities in designated "5.1" areas were "wilderness recreation" and some preservation and commodity activities (Table 4-4). Area "7.1" surrounds the northeastern portion of Lake Monroe and was designated an intensive recreation area. It contains several boat access areas and the Hardin Ridge Recreation Area. Most operational-level activities were related to maintaining or improving the recreational experience (e.g., visual enhancement, recreation facility construction and maintenance) and promoting preservation (e.g., erosion control).

In short, the institutional landscape of the 1960s and 1970s was one that permitted potentially "spectrally sensitive" landcover change activities such as clearcutting for timber, mineral harvesting, and road construction throughout most of Hoosier National Forest's boundaries. Internal Forest Service memoranda provided guidelines on where activities could or could not be undertaken, but these were not formally published. By the late 1970s, public pressure and new legislation created an environment that shifted the emphasis toward multiple use management. At the same time, collective-choice and operational-level authority over forest management practices began to shift away from

Forest Service dominance to more involvement by the citizenry and the Judiciary. The multiple-use management approach mandated by MUSYA, requirements of NFMA and the opportunities brought forth by the Wilderness Act led to a redesign of the Hoosier institutional landscape from legislative "blankets" covering the entire property as a whole to more of an "institutional quilt." Subareas of the Forest were specifically set aside for one or more of the six mandated uses. While certainly well before the 1980s Hoosier forest officials were making decisions with important ecological areas protected in their minds, the formal establishment of the Deam Wilderness area in 1982 marked the first major geographic change to the Hoosier institutional landscape.

This shift toward formal operational-level plans with formally mapped institutional boundaries took many years to materialize. While NFMA mandated this planning in 1976, it took until 1985 for the first Hoosier National Forest Plan, with newly specified management units, to appear. The first plan acknowledges the difficulties in the late 70s and early 80s in generating such a document: "Changes in planning policies and procedures have accelerated during the past few years and will continue into the future. These policies and procedures are evolving so rapidly that changes occur between the start and the finish of individual Forest Plans" (USDA Forest Service, 1985a: vi).

The Hoosier Pleasant Run Unit Institutional Landscape in 1985: "The Land and Resource Management Plan"

The first formal "Land and Resource Management Plan" for Hoosier was published in 1985 and remained active until 1991. During this period, legislation and budget and revenue allocation rules appear to have remained largely as they were throughout the 70s and 80s. NFMA and NEPA continued to be enforced as did K-V Act revenue rules.

What changed in 1985 was the rule boundaries that designate where particular activities can and cannot be done within the Pleasant Run Unit. After several years of work, Hoosier officials, following the additional planning steps and procedures required by NEPA. RPA and NFMA produced an Environmental Impact Statement document (USDA Forest Service, 1985b) evaluating *eight* alternative institutional landscape configurations. Mandated public comment periods were established, responses to public concerns were addressed and in 1985 the first 10 year Land and Resource Management Plan was published (USDA Forest Service, 1985a). The institutional landscape for the Pleasant Run Unit as articulated by this Plan is shown in Figure 4-6 and the specific permitted operational activities for each management area type are summarized in Table 4-5. Areas in the map have numerical designations specifying the types of activities permitted in the area.

A comparison of the pre-1985 institutional landscape (Figure 4-5) to the 1985 institutional landscape (Figure 4-6) reveals several new institutional boundaries designated as: "3.1a," "6.1," and "8.3." Prior to 1985 these areas were designated as parts of the "3.2" management area (Figure 4-5). The "3.1a" management area differs from "3.2" area in that it manages for early successionary wildlife habitat. This suggests that timber cutting (clearcutting or shelterwood activities) will more likely occur in this 3.1a than 3.2 after 1985.

By changing some of the pre-1985 "3.2" area in Figure 4-5 to a 1985 designation of "6.1" in Figure 4-6, forest managers added more emphasis on maintaining habitat in this mature hardwood environment for species sensitive to human activities. A comparison of the particular management guidelines between "6.1" and "3.2" designated areas in the 1985 Plan reveal few differences in activities that are prohibited or permitted. This designation, then, appears to be more of a reminder to Hoosier forest managers to be cognizant of wildlife particularly sensitive to human activity living in areas adjacent to the Deam Wilderness.

The new management area designated "8.3" is set aside for geological, biological, cultural, or other scientific value or an unique area of national or regional significance. In this newly designated area, new and significant activity restrictions have been added in the 1985 Plan.

The Hoosier 1991 Plan Amendment

During the late 1980s it became apparent that too many interest groups were disillusioned with the 1985 Plan (Fischer, Pennington and Tormoehlen, 1993). Controversial forest management issues (e.g., timber cutting, potential for mining, etc.) and unresolved lawsuits led Hoosier officials back to rework Plan designs. Public comment and pressure from Indiana political representatives pushed for a Plan revision that placed more emphasis on forest conservation (see letters provided in USDA Forest Service, 1991b, Appendix A). A Plan Amendment was passed in 1991 with a revised institutional landscape. This new institutional design is provided in Figure 4-7 with its associated management area codes listed in Table 4-6. Note the boundaries in this map are more crisply defined than in the prior two. This is because the GIS coverage used to create this map provides more detail and documents only the property that the Forest Service owns. Within the general boundaries depicted in Figure 4-5 and 4-6, there are locations that are under private ownership. This better delineated 1991 map will be helpful in later analysis to avoid attributing land cover change to public management when in fact the parcel falls under private ownership.

A comparison of the 1985 institutional landscape designated by "the Plan" and this new design designated by the 1991 Amendment reveal once again some significant rule changes. Areas abutting Lake Monroe and some river systems that formerly fell under a 1985 "3.2" designation are now "2.4" in the 1991 management plan. This new designation restricts the option of timber cutting in these areas and emphasizes the higher level of emphasis toward recreation in an undisturbed area along water bodies. It also is a response to public comment and public officials from the nearby city of Bloomington concerned about timber operations in the Lake Monroe watershed.

Other areas designated as "3.2" or "3.1" management areas in 1985 were assigned to the "2.8" category in 1991. The primary differences between the former and the latter designations are: (1) a shift from even-aged timber management to a combination of uneven and even-aged methods; and (2) a shift from "mining is permitted" to a strict no-mining policy. The boundary of the Deam Wilderness area (5.1) has remained the same between the two plans, but the 1991 Amendment now adds the additional restriction of no mining of any kind within its boundaries.

An area in the northern portion of the Pleasant Run Unit, designated category "6.1" in 1985 (Figure 4-6) is designated in 1991 as "6.2" territory. Further, more to the east end of the Unit, the "Nebo ridge" area, designated "3.2" in 1985, was split in 1991 into two separate management areas classified as "6.2" and "6.4" respectively. The old 3.2 designation allowed for timber production and mineral extraction, whereas their current

6.2 and 6.4 designation prohibit these activities with the exception of salvage from naturally produced damage (e.g., tornados). The primary difference between the 6.2 and 6.4 designation is that 6.4 leaves commercial timber operations as a potential option to achieve "desired resource conditions" (USDA Forest Service, 1991b 2-44). These changes between the 1985 and 1991 plan once again reflect the more recent emphasis on the forest as a recreation and "natural preserve" and a move away from forest management with an emphasis on timber extraction.

The area designated in 1985 as "8.3," a unique or "special" area, is in the 1991 Amendment designated as a "back country" area. This in general means it is still subject to highly restricted activities, but for different reasons.

Finally, two management area types falling under the "9.2" designation are identified in the 1991 Plan Amendment that were not designated as such in the 1985 Plan. Category 9.2 designates areas that may provide unique ecosystems and may deserve protection but were unclear at the time of Amendment publication. The 9.2 designation is a holding category until a further decision can be made.

This comparison of the institutional landscapes in Figures 4-5, 4-6 and 4-7 reveals a relatively dramatic shift away from a commodity-based management plan to one managing primarily for recreation and wildlife habitat. Forest officials responded to significant citizen outcry emphasizing this shift. Only in the "2.8" designated areas in 1991 are commercial timber activities still permitted and even in those areas these activities are subject to significant public scrutiny.[33] This 1991 map in Figure 4-7 describes the Hoosier landscape as it continues to be managed today.

A History of the Institutional Landscape and the Incentive Structures of Yellowwood State Forest Property Managers: 1972-1992

A Brief History of the Indiana Division of Forestry and one of its Properties: Yellowwood State Forest

State forestry initiatives in Indiana began in 1894 when the Bureau of Forestry, Horticulture, and Irrigation was created (Fischer, Pennington and Tormoehlen, 1993). Purchasing of the first state forest was authorized in 1903 (Wilcox, 1951) and shortly thereafter Charles C. Deam was appointed as the first official state forester (Kriebel, 1987). In 1919, the State Department of Conservation was created with the Division of Forestry (DOF) as one of its major units (Zumeta, 1980). Four years later, in 1923, the first professional forester was hired (Widner, 1966). The Division of Forestry was assured a stable source of revenue in 1925 when the LaFuze Act was enacted. This Act assigned a portion of state tax money to go to a dedicated forestry fund to be used for purchase and management of state forest properties and for the expansion of the state nursery (Widner, 1966; Favinger, 1984a).

During the 1930s, the state of Indiana began acquiring degraded lands to designate as state forests. The same factors that influenced the decision of where to place the Hoosier National Forest influenced where state forests were purchased: areas of high soil erosion and depressed economic conditions (Mathis, 1936). State property purchases often fell under Resettlement Administration programs, parts of the New Deal program, which worked to assist poor farmers and move them to more agriculturally productive land (Sieber and Munson, 1992). This initiative also helped local governments, for in many resettlement areas, many citizens were delinquent in paying their property taxes and the local governments were facing fiscal crises. By resettling these residents to more agriculturally productive areas, the state government (and federal in the case of Hoosier) could begin to stabilize the land through planting, letting the land convert back into forest. By relocating people, unneeded schools could be closed and some roads could be left unmaintained–thus diminishing the financial burden of local governments. At the same time, the forest areas were seen as a longer term investment (in terms of timber) for the State of Indiana (Wilcox, 1951). There were other benefits to this strategy as well. Many artificial lakes were created in state properties to serve as water recreational areas and to provide available water resources for nearby communities (Outdoor Indiana, 1935b). Yellowwood lake on the Yellowwood State Forest is one such lake (Outdoor Indiana, 1938). State officials felt that these newly formed state managed recreation areas would improve the economy of the surrounding county through tourism.

The initial land forming Yellowwood State Forest was acquired in 1947 by the Department of Conservation (IDNR, 1995).[14] Management activities in State Forests during the 1940s through 1960s were generally devoted to halting erosion and protecting and developing pine and hardwood stands (IDNR, 1995).[15]

Management of state properties in the early 1950s already exhibited a "multiple use" philosophy as shown by the article "The State Forests of Indiana" by Ralph Wilcox, the Indiana State Forester in 1951. In this article Wilcox stresses the same benefits we hear of today: watershed protection, soil rebuilding, wildlife habitat, recreation, and profits from timber production (Wilcox, 1951). After World War II, each state forest was supervised by a full time forester for "forest management and timber operation" (Widner, 1966: 364). For a brief period however, political battles ensued over appropriate property management and "farm foresters" were forced out of the Department of Conservation (Ibid.). Further state property acquisition stopped temporarily. A new governor was elected in 1957 and professional foresters were shortly thereafter appointed back to the helm of state forest properties On July 1, 1965, the Indiana General Assembly established the Indiana Department of Natural Resources (IDNR) to consolidate state agencies involved in natural resource protection. The DOF continues to be one component of the IDNR.

At the time IDNR was created, officials emphasized a need to modify collective-choice activities in order to keep political struggles out of the daily management of State Forests. First, the IDNR established a Natural Resources Commission made up of 6 "lay members," appointed by the Governor, and six ex-officio members. This commission was formed to charter the direction of the IDNR's activities To keep this committee balanced politically, a constitutional-level rule was established that no more than three "lay members" on the commission could be associated with any one political party (Favinger, 1984b). Further, during this time there was a general recognition that the hiring of state forest staff had to be based more on technical merit than political, religious, racial or fraternal organization (Widner, 1966; Favinger, 1984a). This led to the hiring of professional foresters into state property management positions. Today, the Indiana Department of Natural Resources Division of Forestry manages thirteen state forests and three natural recreation areas (IDNR, 1998c). Yellowwood is one of these thirteen forests under Division of Forestry jurisdiction.

The Yellowood Institutional Landscape: 1972-1992

The institutional landscape at Yellowwood has been relatively stable over the 1972-1992 period and is comprised mostly of rules that blanket the entire property

Legislation and Agency Regulations

When compared to the institutional landscape of Hoosier. Yellowwood's is fairly parsimonious in terms of legislation. Indiana code 14-23-1-1 directs DOF management to protect and conserve timber, wildlife, soil, and water resources for current and future generations. This legislation also mandates the Division to manage the forest for timber with the goals of improving the commercial value of the forest, supplying local timber markets and providing revenue to the state and local governments (PL1-1995 16-23-4-1, p. 306)

The 1971 enactment of the State's "Property Manager's Career Act" added an additional level of neutrality and consistency to state property management. This Act ensures that vacancies are advertised, applications are screened by the appropriate division, and the two top candidates are interviewed and selected by the IDNR's Natural Resource Commission. It also helped to establish what appears to be a "professional forester" culture in state forest manager offices.

Revenue Rules and Allocations

Throughout the 1972-1992 study period, the DOF obtained revenue through what could be considered a standard budgetary procedure. Two-year budget requests were submitted from the property level to the Division headquarters. IDNR compiled the complete budget request which was then submitted to the Governor's office. The Governor submitted a full budget to the Legislature. Once the budget was passed, funds were sub-allocated to the Division of Forestry under broad budget items (e.g., personnel, utilities, services, equipment, etc.) (Koontz, 1997).

Internal documentation received from the IDNR reveals that two-year appropriation outlays come from three primary sums of money or funds (IDNR, 1996).[36] First, funds are appropriated from property taxes designated under the 1925 LaFuse Act (Indiana Code 14-23-3-3).[37] Second, money supporting future activities are appropriated from the Division of Forestry's Dedicated Fund. Recreation income (e.g., sport licenses, property admittance and use fees), timber production income (e.g, timber, post, pole and firewood sales), and nursery income contribute to this fund (IDNR, 1987:8; IDNR 1996c). Third, additional money needed to meet budget requests, if deemed necessary by the Indiana General Assembly, is taken from the State's General Fund. For instance, in 1995, one Division official reported that 82% of the total operating budget came from the property taxes and the dedicated fund, and the other 18% came from the general fund (Koontz, 1997: 62).

In his interviews with Indiana state foresters, Koontz (1997), investigating whether property managers and their staff are budget maximizers, reports that Division officials see little budgetary incentives to increase timber production. These officials state that in an instance where timber production is increased, the Dedicated fund will increase. But they argue that this will only cause the Legislature to appropriate less money to them from the General Fund rather than resulting in a larger appropriation for the DOF. The Indiana Legislature, it appears, keeps their budget outlay relatively stable from year to year.

But what Koontz's interviews suggest is that there is, at very high levels of the Indiana Government–*above the property manager's level*–a budgetary incentive to at least continue timber production and recreation in State Forests. In lean budgetary years, it is easily imaginable that the Indiana Legislature appreciates a high DOF Dedicated fund so that more monies of the General Fund can be assigned to other purposes. Koontz's interviews with Division officials support this contention as they admit that when the Dedicated fund is higher, the money appropriated from the General Fund goes down. While the property managers do not see a reason to increase timber production as a means of increasing budget as Koontz reports, it is clear that the Governor and the Indiana Legislature have a real incentive to encourage the DOF to continue to undertake activities–timber production, recreation fees and nursery sales–that increase this Dedicated fund. A larger Dedicated fund based on product sales means legislators have to provide less from scarce General Funds each biennial appropriation period.

Two other statutory requirements also add pressure to DOF property managers to continue timber production activities. First, Indiana Code 14-23-4-5 requires that 15 percent of net timber sale receipts be allocated to the county where the timber was cut in lieu of property tax (IDNR, Division of Forestry, 1996a). In fiscal year 1981-82 for example, Brown County received $18,112 from Yellowwood State Forest from timber sales that year (Duncan, 1983:33). Legislators from particular counties, therefore, have another real incentive to encourage the DOF to keep timber operations going in state forests. Timber sales bring additional tax revenue into counties and establish possible opportunities for Legislators to reduce the amount citizens in their districts pay in taxes or to increase funds available for county spending. Second, in 1984, the Indiana General

Assembly passed a law requiring a portion of the net receipts from state forest timber sales to be allocated to county fire departments (IDNR, 1986: 21). This is another source of revenue for public services that doesn't come from tax payers' wallets.

From this discussion of revenue rules and allocations, it becomes readily apparent that an important component of their multiple use mission as mandated by the Indiana General Assembly is to manage for timber production. An additional benefit of timber production to the state is to assist local industry and employment. One justification for state investment of these forests around the time Yellowwood State Forest was created was the long term return to the citizenry in timber sale proceeds (Wilcox, 1951). The importance of management of State Forest land for timber production is clearly stated in the 1973 IDNR Annual Report: "The object of Indiana Forest Management is to maintain good growing conditions and to keep the land in the most profitable stage of timber production" (IDNR, 1973: 50). This emphasis continued throughout the late 1970s and 1980s. For example, Zumeta's article describing a 1980 State Forest planning initiative emphasized the importance of this industry to Indiana's economy:

> The importance of Indiana's forest lands warrants such a [planning] effort. These forest lands provide diverse outdoor recreation opportunities and wildlife habitat, as well as the resource base for a thriving timber industry. Indiana's timber industry is one of the State's seven largest industries. It employs 50,000 people and accounts for *three billion dollars* of economic activity annually (his emphasis) (1980: 32).

Table 4-7 presents some additional evidence of the multiple use strategy and the continued timber production on Indiana State Forests. This table is compiled from available data from two different sources. For most of the 1970s, IDNR annual reports contain this data. Unfortunately, some of the annual reports for the 1980s were unavailable in public records. Therefore, most of the 1980s data are compiled from DOF records obtained by Koontz during his research (Koontz, 1997). This table supports the DNR statements that they are managing for multiple use. It also shows that receipts from product sales contributes significantly to the Division's Dedicated Fund–certainly appreciated by the Indiana General Assembly as they grapple with appropriation strategies while striving to lower taxes.

Planning Documents and Standard Operating Procedures

Unlike at the federal level, no legislation has been enacted in Indiana that directs the DOF to undertake formal forest management planning. Yet DOF officials have taken initiative in conducting planning (Koontz, 1997). In 1966, the Division initiated a State Forestry Planning Committee (SFPC) to assist in coordination of various state agencies involved in forestry and conservation. People serving on this committee represent "all major interests in the state who managed or used forest resources" (Fischer, Pennington and Tormoehlen, 1993: 29). This committee assisted the Division in developing Indiana's first statewide forest resource plan in 1981 (Zumeta, 1981). While this committee has been used to recommend strategies, it does not have formal authority to formulate state forest policy. The Division sees its role more "to promote communication and understanding of forest management issues, support sustainable forest resources, and encourage improved forest management practices (Fischer, Pennington, and Tormoehlen, 1993: 29).

While there were planning documents and standard operating procedures during the 1970s, these existed in the form of individual memos and small internal documents that are not easily found or accessible today. Documents produced by the agency during that decade (e.g., IDNR, Division of Forestry, 1978) reveal a professional forest division with standards for timber operations even though, unfortunately, such standard procedures and protocols were not consolidated into one working document (Allen, 1996). The professional foresters during the 1970s in Yellowwood worked under a developed set of standards, e.g., defined allowable cuts based on forest type, condition and silviculture requirements (IDNR, Division of Forestry, 1973-1980). For example, sometime in the 1970s, the DOF mandated that only intermediate cuttings (improvement, salvage and thinning cuts), group selection (½ to 5 acres in size) or single tree selection methods would be used. (This silviculture mandate will be important later as we explore the impact of cutting outcomes on satellite images.) The institutional landscape during the 1970s was therefore largely one set of rules (e.g., the legislation, revenue rules and allocations and guidelines on appropriate silviculture techniques) that cover the entire Yellowwood landscape. No "special use" designations appear to exist within the property during the 1970s after a careful review of Yellowwood records.

During this time, however, an administrative landscape did exist–an important component of the Yellowwood institutional landscape. Operations within Indiana State Forests were, and continue to be, managed using a "tract" system. A tract is an administrative boundary that the forest property manager maintains to record past and present operational-level activities that have occurred within the property. Periodically, as new areas have been purchased from neighboring private owners, tract boundaries have been revised. But these tract revisions appear to be for mostly administrative purposes and during the 1970s and 80s do not appear to specify different rule configurations.

Consequently, only the Yellowwood's tract landscape as it exists today will be used in later analysis (Figure 4-8).[38]

Beginning in 1980, the DOF took it upon itself to create a more formal planning operation and a State Forest Plan (Zumeta, 1980, 1981). The goal of this was to develop systematic direction for forest programs (both public and private) for the 1981-1988 time period. Specifically regarding State Forest property management, the plan emphasized: (1) timber inventories and the development of a comprehensive land management plan for the property; (2) a roughly 50% increase in road construction and maintenance activities in 1988 over 1980 levels; (3) an increase in insect and disease control and information and educational activities by 34% and 73% respectively; and (4) a 108% increase in income in 1988 over 1980 derived mostly from more intensive timber harvesting on designated timber production areas. The goal was to increase the amount of state forest produced revenue to pay for operation and maintenance of the property (Zumeta, 1981: 36). Yellowwood was one of the properties subject to meeting these new goals.

Unlike NEPA and NFMA at the national level, there is no Indiana State legislation requiring public input into the forest planning process (Koontz, 1997). However, in the process of developing this Plan, the DOF did solicit public input. A thirty-five member "Citizens' Advisory Committee" and a thirty member "Technical Advisory Committee" were formed to help develop the plan. Further, a survey was sent to 1,284 citizens and 607 interest group representatives asking their opinions about state forest management, and the 1,000 returned surveys were used in planning. A draft Plan was published in 1981 with three program direction alternatives and a public comment period was provided. After reviewing comments provided by the public and the advisory committees, the State

Forester chose a management alternative and the final planning document was published (Zumeta, 1981). It is important to emphasize, however, that Indiana has no legislation requiring a formal public appeal process in the development of management plans. The public input the DFO does receive is solicited by their own initiative and discretion. Interest groups such as conservationists have no legal authority (e.g., an appeal process) to stop operational-level activities.

Individual tract inventories and plans were developed during the 1980s and continue today. In 1983, a property-wide continuous forest inventory was conducted at Yellowood in order to define allowable cuts for tracts (IDNR, Division of Forestry, 1995). Tract inventory sheets, resource management guides, sale records, and in some cases topographic maps delineating timber cut locations are contained within tract folders. The resource management guides document forest property manager and staff decisions about what activities are permitted in the tract (e.g., timber harvesting, recreation, wildlife habitat maintenance), and what activities should be done in the future to enhance tract management goals (e.g., harvest, timber stand improvement, erosion control, etc.). These plans are based on inventory information, aerial photographs, soils information, adjoining land uses, wildlife concerns, recreational use of the tract, riparian zones, professional knowledge, and cultural and special areas identified within the tract (IDNR, 1996d). It also contains an "accomplishment record" that allows forest property managers a mechanism to document when and what types of management activities were undertaken.[39]

Consequently, the management planning during the 1980s and early 1990s produced a more complicated institutional landscape at the tract level. As of 1995, Yellowwood State Forest is 23,356 acres in size. Most of this acreage is designated multiple use and

16,047 acres are designated "commercial," meaning that they can be managed for timber production. The designated annual allowable cut for the entire property is 673 acres. 584 acres are designated "old forest" and another 801 acres are designated "back country" recreation. Another 35 acres are designated as nature preserves, 12 acres are used to produce straw, 85 acres are "open fields" and 5,792 acres are designated "other non commercial forest" (e.g., wetlands) (Allen, 1996b).

What isn't available, unfortunately, is a comprehensive map of the property from the 1972-1992 period that designates where certain activities were permitted, required or prohibited–similar to what the Hoosier Plan and Plan Amendment provided.[40] But from a review of the tract files and from the 1995 summary data provided in the paragraph above, it appears that most tracts were designated multiple use, where recreation (e.g., hiking, hunting, etc.) and timber production activities were permitted. Internal records show that during the 1970s and 1980s, several tracts were excluded from "allowable cut" acreage because they (1) were too difficult to access (e.g., for topographic reasons); (2) had low value vegetation (e.g., pine); (3) were adjacent or encompassed designated recreation areas (e.g., campgrounds); (4) were adjacent to private property; (5) contained older vegetation that the property manager wanted to preserve; or (6) were important visual enhancement areas (e.g., can be seen from a road or Yellowwood lake) (Allen, 1996b). While these may not be mapped, knowledge of these strategies will be helpful in later satellite image analyses.

In summary, the Yellowwood institutional landscape appears to have been more consistent over the 1972-1992 time period then that of Hoosier. Most areas within its boundaries have permitted both recreational activities and timber production activities.

And while the DOF has a demonstrated management philosophy with an interest in supporting recreation, wildlife habitat, cultural heritage protection, and watershed management, they continue to be faced with legislation-based incentives to undertake timber production activities.

Generating Testable Hypotheses

With both Hoosier and Yellowwood's institutional landscapes described, we can now generate testable hypotheses related to property manager activities.

As stated earlier, both the Pleasant Run Unit in Hoosier and Yellowwood coexist in generally the same physical landscape–the Brown County Hill region (Homoya, 1997) Both forests comprise mostly Oak-Hickory and Beech-Maple type stands with a scattering of pine planted by the CCC in restoration efforts. Both Forests serve generally similar community landscapes. It can be assumed that their user base is largely people from the state of Indiana (for Yellowwood, see Caylor and O'Leary, 1995), with many visitors coming from many of the nearby surrounding counties. In addition, they both are interspersed with private property located within their general boundaries. They both serve a similar citizen base and interact with the similar interested parties, timber companies, timber industry associations and environmental groups. Further, both organizations appear to be staffed with people with predominantly professional forestry or forest ecology educational backgrounds.

Given these attributes, the physical and community landscapes in these two forests have remained similar over the 1972-1992 period. While the community landscape may have changed over time, it has largely changed in the same way for both forests. However, there are important differences in their institutional landscape configurations and histories.

Hypotheses Related to Change in the Pleasant Run Unit of the Hoosier National Forest

Over this twenty-year period, property managers in the Hoosier have faced a changing institutional landscape that has altered their cost/benefit calculus related to activity preferences. The incentive structures established in Washington D.C. through legislation and through agency revenue rules and allocations led Forest Service officials to emphasize timber extraction during the 1960s and 70s. Benefits were higher than the costs in undertaking timber production activities. Clearcutting, the silviculture method of choice, meant that large forest openings were cut during those decades. New legislation in the 1970s and 80s emphasized more of a multiple use philosophy and forced property managers into a planning process requiring public input. Legislation also provided interest groups with a vehicle to formally appeal management decisions through the court system. These mandates raised the expected costs of timber cutting significantly while at the same time raising the expected benefits of undertaking recreation, wildlife habitat preservation and forest protection activities.

Maps provided in the 1985 and 1991 Plan documentation allow the generation of specific hypotheses about the spectral trajectories of Hoosier Pleasant Run Unit (HPRU) management. Four areas exist with different institutional histories: (1) Deam Wilderness; (2) Areas adjacent to Deam that are more protected than they once were (e.g., "6.1," "6.2" in 1991); (3) Intensive recreation areas; and (4) Areas designated "2.1" in 1991 that in 1991 continue to permit cutting activities.

HPRU Hypothesis 1: Vegetation in the protected area of Deam Wilderness (area "5.1" in Figures 4-5, 4-6 and 4-7) will begin to show patterns of natural regeneration and little or no evidence of human activity.

HPRU Hypothesis 2: Areas designated as "3.2" (multiple use) prior to 1985 (refer back to Figure 4-5) that later were designated as "6.1" or "8.3" in 1985 (refer back to Figure 4-6) and "6.2" in 1991 are expected to show patterns of natural regeneration.

HPRU Hypothesis 3: Areas managed for intensive recreation (e.g., "7.1" in Figures 4-6 and 4-7) are expected to reveal a higher level of stable exposed soil, perhaps some new forest to soil conversion for new facility development, and natural regeneration in the form of mature canopies protected for visual enhancement.

HPRU Hypothesis 4: Areas that have been designated as "multiple use" over time (e.g., 2.8 in Figure 4-7 that prior were designated 3.1 or 3.2) are expected to reveal mixed spectral trajectories, exhibiting some limited patterns of cutting and access road construction. Given the intense pressure the Forest Service has received from the public in the mid-1980s and 1990s over cutting initiatives, it is expected that spectral patterns of cutting in these areas will exist, but in limited areas.

Hypotheses Related to Change in Yellowwood State Forest

Over this twenty year period, the institutional landscape in Yellowwood has remained more consistent than that of Hoosier. It too has had a multiple-use mandate and forest records clearly reveal a management strategy following that philosophy. What is different in Yellowwood is that it has not been faced with legislation mandating public particpatory planning with mechanisms where public protests can be taken to the courts.

Thus, property managers in state forests, face a very different incentive structure compared to those in national forests. They accrue benefits in undertaking all of the multiple use management activities: recreation, wildlife habitat maintenance, watershed management and timber production. Over time, the expected costs of undertaking timber production activities have increased slightly but only because the DOF took it upon itself to bring in some public input into management plan development. The statutory environment that has existed over the twenty year period continues to keep expected benefits for maintaining timber production activities higher than expected costs. Legislators, wanting to keep taxes low while still striving to balance the state budget or produce a surplus, keep statutes intact that allow product receipts to fill the Division's Dedicated fund. High level officials in the DOF and property managers are expected to follow this mandate.

While no map exists currently that delineates areas of special protection, the following hypotheses can be generated:

> *YW Hypothesis 1: High intensity recreation tracts will exhibit mixtures of vegetation and soil reflectance. Vegetation canopies in these areas and areas surrounding Yellowwood Lake will have a natural regeneration spectral trajectory over 1972-1992 as they are left untouched for visual enhancement purposes.*

And, alternatively,

> *YW Hypothesis 2: Tracts that are relatively easily to access and are not (1) directly adjacent to Yellowwood lake, (2) used for intensive recreation (e.g., campgrounds), or (3) containing a high number of pine stands, will exhibit signs of timber production activities over the 1972-1992 period.*

Finally, hypotheses can be made in regard to comparing landcover change in the Pleasant Run and the Yellowwood Forest areas. Given the differences in public participation and revenue rules and allocations between Hoosier and Yellowwood, the following statement can be made:

> *HPRU-YW Hypothesis 1: Given what we know about the incentive structures guiding property manager decision-making between 1972 and 1992 it is expected that Yellowwood will exhibit a higher level of human disturbance activities, particularly in terms of timber cutting, than anywhere in the Hoosier Pleasant Run Unit.*

Conclusion

This chapter has outlined the incentive structures Indiana State and National Forest property managers have faced over the 1972-1992 time period, described their probable activities, and presented some testable hypotheses related to landcover outcomes. These hypotheses will be tested using a time series of Landsat multispectral scanner images later in Chapter 7. But first we need to investigate the sensitivity of these images to common human activities in the south-central Indiana region. To do this requires an overview of the remote sensing analytic technique I intend to use. This is described in Chapter 5. Subsequently Chapter 6 undertakes a "sensitivity analysis" of the satellite image time series using another state forest—Morgan Monroe—as a reference.

Chapter 4 Endnotes

1 This is, in fact where my colleagues at the Center for the Study of Institutions, Population and Environmental Change (CIPEC) and I are headed. In addition to this study, we continue to accumulate research related to institutional form and outcomes for other property regime types (see, for example, Koontz, Carlson and Schweik, 1998; and Gibson and Koontz, 1998). Recently, my colleagues and I have initiated a major study of non-industrial private property owners in south-central Indiana with the hope that by years end 1998 or early 1999 we will have surveyed and analyzed the incentive structures of 200 or more private property owners and linked their past activities to change in a temporal set of satellite images. One of our hopes is to provide information to the Indiana Division of Forestry on what is driving forest change under private property regimes and how the Division might improve their private forest owner assistance programs.

2 The categories "large," "medium," and "small" used in this chapter have been defined through consideration of the Landsat MSS pixel size and their likelihood that they will be identified on a satellite image. An MSS pixel is approximately 79 meters by 56 meters, about 1.1 acres or slightly less than a U.S. football field (Campbell, 1996). "Large" development activities I categorize as ones that have disturbed 10 acres or more of the landscape—roughly 9 Landsat MSS pixels would be disturbed. "Medium" scale development activities are ones that disturb landscape areas less than 10 acres but greater than 1 acre (between one and eight MSS pixels). "Small" scale develop are activities that impact one acre or less (some or all of one MSS pixel).

3 See, for example, Wilkie and Finn's (1996) discussion on detectability and recognizability in satellite images. This will be discussed in more detail in Chapter 5.

4. Hunting policies in the Brown County State park in southern Indiana provide another good example. For a long period of time this Park has maintained a "no hunting" rule. The result has been a burgeoning deer population and a significant loss in understory vegetation. Subsequently, the deer population began to starve, and the policy changed to allow an annual 3-day per year "hunting weekend" to control the growth of this deer population. It is quite likely that this long term no hunting policy may have produced significant differences in the way the vegetation in this park has been able to regenerate, leaving a higher proportion of older trees with fewer younger ones in the understory. It is an empirical question whether this forested area, compared to one with less of a deer problem, actually exhibits differences in light reflectance properties. But it provides a good example of how a long term operational-level recreation rule might significantly impact forest condition and structure.

5 Stand preparation actions can however be quite large. Just recently in the Hoosier National Forest the forest service has begun salvage logging sales of an estimated 3 million board feet of timber damaged by a tornado (Hinnefeld, 1996).

6. An example of this is the dramatic number of pine stands, planted in the 1930s and 1940s by the Civilian Conservation Corp, that now are easily identified on satellite images. These are not indigenous to this part of Indiana.

7. A "pixel" is the smallest unit of data contained in a satellite image. More discussion of this will follow in the next two chapters.

8. Five methods of thinning are commonly used and this discussion is taken largely from Smith (1962): (1) low thinning, (2) crown thinning, (3) selection thinning, (4) mechanical thinning and (5) free thinning. "Low thinning" is a technique that removes trees hidden below the canopy or predominantly engulfed in the canopy. "Crown thinning" involves removal of upper crown class trees to make room for other good quality existing trees of the same class. "Selection thinning" takes a radically different approach. It involves the removal of the dominant trees in the canopy, in order to encourage the growth of subordinate trees. "Mechanical thinning" is more of a systematic approach to thinning, where trees are removed in a predetermined pattern with little consideration of the tree's position in the canopy. Finally, "free thinning" describes the technique where selected cutting is done without regard to the tree's position in the canopy. The degree to which thinning practices will be revealed in satellite imagery will depend on the extent to which thinning is conducted (that is, how many trees are removed), the number of times thinning activities are conducted, and the types of understory species that remain to fill in the gaps.

9. For example, there are a number of well documented lawsuits in the Morgan-Monroe office records which involve illegal encroachment and removal of timber along the edge of a property boundary by adjacent private property owners.

10. I base this comment on my own research looking through records of the Morgan Monroe and Yellowwood State Forest properties.

11. See Eggertsson (1990), Firmin-Sellers (1994), E. Ostrom (1990) for further discussion of the New Institutionalism and examples of how it has been applied.

12. In situations where operational rules are strictly enforced, the potential cost to the actor himself or herself for breaking a rule could be considered quite high. The actor's anticipated cost of being caught may influence greatly the actor's decisions to undertake or not undertake such an action.

13. A "tract" is a general management boundary used by state foresters in the region. It traditionally takes its form as a result of a land purchase (e.g., a new parcel is added to the property) or it is spatially delineated by some physical feature such as a road, stream or some other physical landscape component. It is the state forest's primary unit for management record keeping.

14. In my work reviewing state property records, several tract files had letters to owners of neighboring parcels describing the activities that were planned. The state property

manager is attempting to maintain a "good neighbor" policy by keeping these residents informed of future planned activities in parcels adjacent to their properties.

15. I've modified slightly Koontz's (1997:9) terminology. I interpret his "regulations" to capture both executive orders along with agency defined standard operating procedures.

16. My research in the Morgan-Monroe forest provides an interesting example that is directly relevant to what we see in the satellite images. One of the lakes on the property, Bean Blossom lake, was created decades before 1970 using a dam. Sometime in the late 1980s or 1990s, the dam collapsed causing the lake to be destroyed. What once was a significant water body is now, in 1998, a very early successionary forest. While the foresters would like perhaps to rebuild the dam and restore the lake, they don't have the available funds to take on that activity.

17. I have had a number of opportunities to be in the field with some of the state foresters in this region and have been particularly impressed with the level of care they show toward forest vegetation and wildlife. These professionals exhibit a concern for the forests and a love of being outside and have given me the impression that they have a sincere desire to undertake management practices that maintain a "healthy" forest in terms of vegetation diversity, age, wildlife, etc., while responding to the incentive structures placed on them by higher level officials.

18. Indiana's Department of Natural Resources Division of Forestry, working with timber harvesters, foresters, buyers, land owners and forest conservationists, have recently produced guidelines on "best management practices" that are based, in part, on scientific research (IDNR Division of Forestry, 1996d).

19. What physical differences are not similar between the two forests will be controlled for using Geographic Information Systems, most notably, a digital elevation model and corresponding products (e.g., slope, aspect coverages).

20. One forester, who worked in the Hoosier National Forest during the 1930s and saw the erosion and gully problems first hand, remarked that the only topsoil left was "in the Ohio River" (Sieber and Munson, 1992: 89).

21. Interestingly, the announcement of this initiative in the February 1935 issue of Outdoor Indiana stresses the importance of this new area for recreation without mentioning of the use for timber production. Given that most of the land was abandoned agriculture, there were probably few areas that had trees of merchantable size available at the time it was designated, so this option doesn't appear to have even been considered in the early days of the Forest.

22. Only the Hoosier areas that lie in the satellite overlap region are shown in this Figure. The Tell City Unit, for example, falls in a more southern region of Indiana that is not shown on this map.

23. Black Locust was a hardwood species also planted in the 1930s to control erosion, but years later it was found to be susceptible to insect and disease damage. It did prove to increase the nitrogen content of soils where it was planted (McCleerey, 1977).

24. As mentioned in Chapter 1, a third level of institutions, "constitutional-choice," is also an important component that determines how collective-choice rules are developed (Ostrom, Gardner and Walker, 1994). This level of institutions is important in ultimately determining what occurs on the ground, but indirectly. Understanding the Hoosier National Forest history at this institutional level is beyond the scope of this study.

25. 30 USC 34, 35, 36.

26. A summary of significant laws that must be considered in planning national forest activities can be found in the beginning of the 1985 Land and Resource Management Plan for the Hoosier National Forest. Further information is supplied in a U.S. Department of Agriculture Handbook entitled "The Principal Laws Relating to Forest Service Activities."

27. Multiple Use-Sustained Yield Act of 1960, 74 Stat. 215.

28. I conducted a review of all the Hoosier National Forest management documentation held at Indiana University's Government Publications library, which holds a substantial inventory. With the exception of two documents related to oil and gas leasing and off-road vehicle policies, no other planning related documents were found. No major planning documents from the 1960s or 70s appear to be stored at the Hoosier National forest main office either aside from office memos and other short documents related to projected or actual timber volumes for cutting activities (Turney, 1998).

29. NFMA, section 14(h) (16 USC 472a).

30. NFMA, section 18 (16 USC 576b).

31. See Koontz (1997) for more discussion, including a contrary argument that, in his research, national forest officials in 1995 did not appear to be strongly motivated by revenue incentives to emphasize timber.

32. For example, by 1982 oil and gas lease applications had been received for more than 80 percent of the Hoosier National Forest area (USDA Forest Service, 1985a: 3-3).

33. Recently, in 1996 (which is beyond the scope of this study) the Hoosier National Forest officials have faced significant challenges to the permitted activity of "timber salvage" that remains in many of the Pleasant Run Unit management areas. Interestingly, one of the tornado damaged areas falls under the "2.8" designation, an area where timber cutting is still permitted (USDA, Forest Service, 1996). Challenges to the salvage activities have made front page news in the local papers. This provides a good example of the kinds of public pressures the Forest Service has been under to cease commercial timber activities in the Forest.

34. Purchase criteria in the 1950s included: (1) amount of land available for reforestation. (2) trend of soil depletion; (3) extent of school loan delinquency; (4) cost of the taxpaying public in maintaining roads and schools in scattered population districts; (5) cost per acre; and (6) desire of existing owners to move their labor and capital to more productive land areas (Wilcox, 1951: 2).

35. Interestingly, it appears that in some instances, forest land was purchased that wasn't subject to soil degradation although most literature published at the time emphasizes this In my research, I reviewed aerial photographs of the Yellowwood lake region in the late 1930s, 40s and 50s and much of the land surrounding the land was well stocked with what appear to be reasonably mature trees. The 1939 photograph, for example, is shown in Chapter 5, Figure 5-1 A).

36. This documentation was collected by Koontz (1997) during his research. I am indebted to him for providing me access to materials he collected.

37. Initially the property tax was one-half mil (5% of $.01) on each $100 of taxable valuation (Favinger, 1984a) As of 1995, it was set at 6 and one-half mils or 65% of $.01 per $100 assessed valuation (IDNR, Division of Forestry, 1996c).

38. This is different from the Hoosier Plan maps for the boundary changes there specify different rule configurations

39. The Division of Forestry has made even more planning and management advances in more recent years. In 1995, officials published a "State Forest Procedures Manual" to document administrative procedures and to develop more consistent methods across State Forest properties (IDNR Division of Forestry, 1995) They also are in the process of creating GIS systems for each property.

40. The Yellowwood property manager and the IDNR are currently active in developing a relational database and a Geographic Information System to assist them in their property management. Much of the system is already in place, but reflects the management plans as of 1997-98. These plans are beyond the scope of this study (1972-1992).

Table 4-1: Preservation Interest Related Activities

Action	Likelihood that the action is captured on satellite imagery
Preservation and Protection	
Large-scale preservation	
Preservation > 10 acres (roughly 9 MSS pixels)	Probable
Medium-scale preservation	Possible
Preservation > 1 < 10 acres (between 1 and 9 MSS pixels)	
Small-scale preservation	Doubtful
Disturbance < 1 acres (one pixel or less)	
E.g., housing/commercial development, small agriculture, quarry, etc.	

Table 4-2: Recreation Interest Related Activities

Action	Likelihood that the action is captured on satellite imagery
Preparation/maintenance actions related to recreation	
Road and trail maintenance/construction	Doubtful
Campground construction	Doubtful
Recreation actions	
Horseback riding.	Possible
Recreational vehicle riding	Possible
Mountain-biking	Doubtful
Hiking	Doubtful
Hunting/no hunting	Possible
Camping	Possible
Esthetic enjoyment from Vehicles	No
Religious practices	No

Table 4-3: Development Interest Related Activities

Action	Likelihood that the action is captured on satellite imagery
Development and Mining	
Large-scale development	
Disturbance > 10 acres (roughly 9 MSS pixels) e.g., housing/commercial development, golf courses, conversion to agriculture, forest to quarry, etc	Probable
Medium-scale development	Possible
Disturbance > 1 < 10 acres (between 1 and 9 MSS pixels) E.g., road construction, utility lines, housing/commercial development, conversion to agriculture, quarry, etc.	
Small-scale development	Doubtful
Disturbance < 1 acres (one pixel or less) E.g., housing/commercial development, small agriculture, quarry, etc.	
Other External Commercial Activities	
E.g., effects of Industrial emissions/waste	Possible
Silviculture and Forest Management	
Stand Area Preparation	Possible
Slashburning	
Mechanical treatments	
Chemical treatments	
Regeneration (Planting)	Possible
Stand Tending and Protection	Possible
Intermediate Thinnings	
Low thinning	Possible
Crown thinning	Possible
Selection thinning	Possible
Mechanical thinning	Possible
Free thinning	Possible
Even-aged Cutting	
Clearcutting	Probable
Seed tree	Probable
Shelterwood	Probable
Strip or Patch cutting	Probable
Uneven-aged Cutting	
Clearcutting	Possible
Seed tree	Possible
Shelterwood	Possible
Group selection	Possible
Single tree selection	Doubtful

Table 4-4: Management Areas in Hoosier National Forest Pleasant Run Unit Prior to the Establishment of the 1985 Land and Resource Management Plan

Management Area	Desired Services	Permitted Activities
3.2	- Wildlife habitat in mature hardwood environment - Timber (hardwoods) on a sustained yield basis - Recreation in a "moderately natural" environment	Preservation Related Activities - Wildlife habitat management (particularly for those needing mature or over mature hardwoods) Recreation Related Activities - Road and trail maintenance, Campground construction, Hiking, Hunting, Horseback riding, Esthetic enjoyment from vehicles ("Visual quality objectives" established) Commodity/Development Related Activities - Development and Mining Surface disturbing exploration, oil and gas (in restricted areas) Road construction (public and logging roads) Buildings to "support resource management objectives" - Silviculture and Forest Management Regeneration (planting) Stand Tending and Protection (Timber Stand Improvements) Intermediate Thinnings Even-aged Cutting (Clearcut and shelterwood)
5.1	- Natural vegetative succession unaltered by people - Wildlife habitat for animals intolerant of people - Wilderness recreation area	Preservation Related Activities - Large scale preservation, Prescribed burnings Recreation Related Activities - Hiking, backpack camping, horseback riding, hunting, fishing, forest product gathering (e.g. mushrooms), esthetic enjoyment Commodity/Development Related Activities - Mining (only with no surface disturbance)
7.1	- Intensive recreation area	Preservation Related Activities - Erosion control activities[18] Recreation Related Activities Road and trail maintenance and construction, hiking, esthetic enjoyment from vehicles Commodity/Development Related Activities Possible large-, medium-, or small-scale development for recreation assistance Stand tending and protection (To enhance recreational activities)

Table 4-5: Management Areas in Hoosier National Forest Pleasant Run Unit As Documented in the 1985 Land and Resource Management Plan

Management Area	Desired Services	Permitted Activities
3.1A	- Wildlife habitat for early successional wildlife species - Timber (hardwoods) on a sustained yield basis - Recreation, particularly hunting, in moderate amounts	Preservation Related Activities - Wildlife habitat management (particularly for those needing sawtimber sized hardwoods and early successionary habitat) Recreation Related Activities - Road and trail maintenance, Camping, Hiking, Hunting, Horseback riding, Esthetic enjoyment from vehicles ("Visual quality objectives" established) Commodity/Development Related Activities - Development and Mining Surface disturbing exploration, oil and gas (in restricted areas) Road construction (public and logging roads) Buildings & structures may be constructed to "support resource management objectives" - Silviculture and Forest Management Regeneration (planting) Stand Tending and Protection (Timber Stand Improvements) Intermediate Thinnings Even-aged Cutting (Clearcut and shelterwood) - Utility transmission corridors permitted
3.1B	- Same as 3.1A except off-road vehicle use is allowed on designated trails	Same as 3.1A except recreation includes off-road vehicle use

Table 4-5: Management Areas in Hoosier National Forest Pleasant Run Unit As Documented in the 1985 Land and Resource Management Plan

Management Area	Desired Services	Permitted Activities
3.2	- Wildlife habitat in mature hardwood environment - Timber (hardwoods) on a sustained yield basis - Recreation in a "moderately natural" environment	Preservation Related Activities - Wildlife habitat management (particularly for those needing mature or over mature hardwoods) Recreation Related Activities - Same as 3.1A Commodity/Development Related Activities - Same as 3.1A except that utility corridors are not emphasized
5.1	- Natural vegetative succession unaltered by people - Wildlife habitat for animals intolerant of people - Wilderness recreation area	Preservation Related Activities - Large scale preservation - Prescribed burnings Recreation Related Activities - Hiking, backpack camping, horseback riding, hunting, fishing, forest product gathering (e.g., mushrooms), esthetic enjoyment Commodity/Development Related Activities - Mining (only with no surface disturbance)

Table 4-5: Management Areas in Hoosier National Forest Pleasant Run Unit
As Documented in the 1985 Land and Resource Management Plan

Management Area	Desired Services	Permitted Activities
6.1	- Wildlife habitat for species requiring mature hardwood environment and are sensitive to human activities - Timber (hardwoods) on a sustained yield basis - Recreation in a "moderately natural" environment	Same as 3.2 with heavier emphasis on maintaining wildlife habitat requiring mature hardwood environments for species sensitive to human activities.
7.1	- Intensive recreation area	Preservation Related Activities - Erosion control activities Recreation Related Activities - Road and trail maintenance and construction - Hiking, esthetic enjoyment from vehicles Commodity/Development Related Activities - Possible large-, medium-, or small-scale development for recreation assistance - Stand tending and protection To enhance recreational activities
8.3	- Preservation of unique geological, biological, ecological, cultural or other scientific value - Protection of unique area of national or regional significance	Preservation Related Activities - Types of protection activities depend on the attributes of each particular site. Recreation Related Activities - Hiking (if not damaging to the area) Commodity Related Activities - Silviculture systems can be used but must be consistent with guidelines developed for particular types of special areas.

Table 4-6: Management Areas in Hoosier National Forest Pleasant Run Unit As Documented in the 1991 Land and Resource Management Plan Amendment

Management Area	Desired Services	Permitted Activities
2.4	- Wildlife habitat in closed canopy, in mature hardwood forest - Forest buffer along shorelines of at least 1 mile - Recreation	Preservation Related Activities - Natural succession emphasized in this area. Only limited manipulation of vegetation. - Protection of vegetation in riparian areas Recreation Related Activities - River/lake access, boating, canoeing, hunting, trapping, fishing, hiking - Road and trail maintenance Commodity/Development Related Activities - Timber salvage is the only permitted activity but only with "full public involvement."
2.8	- Wildlife habitat for animals using hardwood trees in a mosaic of different aged forest - Timber management - Recreation	Preservation Related Activities - Wildlife habitat management - Riparian area protection Recreation Related Activities - Road and trail maintenance - New trail construction - Hunting, hiking, horseback riding, mountain biking, esthetic enjoyment activities Commodity/Development Related Activities - Silviculture and Forest Management Regeneration (planting) Stand Tending and Protection (Timber Stand Improvements) Intermediate Thinnings Uneven and even-aged Cutting (group selection, shelterwood, clearcuts all permitted)

Table 4-6: Management Areas in Hoosier National Forest Pleasant Run Unit As Documented in the 1991 Land and Resource Management Plan Amendment

Management Area	Desired Services	Permitted Activities
5.1	- Natural vegetative succession unaltered by people - Wildlife habitat for animals intolerant of people - Wilderness recreation area	Preservation Related Activities - Large scale preservation Recreation Related Activities - Hiking, backpack camping, horseback riding, hunting, fishing, forest product gathering (e.g., mushrooms), esthetic enjoyment Commodity/Development Related Activities - none
6.2	- Wildlife habitat for species requiring mature hardwood environment - Recreation in a "backcounty-like" environment	Preservation Related Activities - Large-scale preservation - Wildlife habitat management (for endangered, threatened or sensitive species) Recreation Related Activities - Hunting, fishing, hiking, mountain biking, horseback riding , esthetic enjoyment - Trail maintenance Commodity/Development Related Activities - Timber salvage only and with full public involvement
6.4	- Wildlife habitat for species requiring undisturbed, mature forests - Recreation in a "backcounty-like" environment - Area moving toward old growth (Climax) condition	Preservation Related Activities - Large-scale preservation - Wildlife habitat management (for endangered, threatened or sensitive species) - Barrens, Glades and other natural dry forest communities may be restored Recreation Related Activities - Hunting, fishing, canoeing, hiking, mountain biking, horseback riding, esthetic enjoyment - Trail maintenance Commodity/Development Related Activities - Commercial timber or other timber activities not planned except where the use is determined to be the best way to provide desired resource conditions.

Table 4-6: Management Areas in Hoosier National Forest Pleasant Run Unit As Documented in the 1991 Land and Resource Management Plan Amendment

Management Area	Desired Services	Permitted Activities
7.1	- Intensive recreation area	Preservation Related Activities - Erosion control activities Recreation Related Activities - Road and trail maintenance and construction - Hiking, horseback riding, hunting in designated areas, esthetic enjoyment from vehicles Commodity/Development Related Activities - Possible large-, medium-, or small-scale development for recreation assistance - Stand tending and protection To enhance recreational activities
9.2	- Holding category - Possible preservation of unique geological, biological, ecological, cultural or other scientific value but needs further study	Preservation Related Activities - Large- or medium preservation Recreation Related Activities - Hiking, horseback riding if conditions are favorable for it Commodity Related Activities - None

Table 4-7: Product Sales and Recreation Receipts for Indiana State Forests by Fiscal Year
(Sources: * Indiana Department of Natural Resources, Annual Reports
† Division of Forestry Documentation)

Fiscal Year	Receipts from Product Sales[1]	Recreation Receipts
1972-73*	$118,297 (1,523,665 bd ft.)	$180,022
1973-74*	$194,983 (2,637,718 bd ft.)	$182,566
1974-75*	$225,518 (3,234,765 bd ft.)	$223,186
1975-76*	$264,458 (bd ft unknown)	$281,628
1976-77*	$276,825 (1,746,000 bd ft.)	$238,797[2]
1977-78	not available	not available
1978-79*	$417,041 (2,700,000 bd ft.)	$274,927
1979-80*	$344,591 (2,192,776 bd ft.)	$213,258
1980-81*	$408,017 (2,345,647 bd ft.)	$275,823
1981-82	not available	not available
1982-83	not available	not available
1983-84	not available	not available
1984-85†	$1,011,580	$358,461
1985-86†	$1,046,383 [3]	$279,361
1986-87†	$1,489,756 [4]	$507,640
1987-88†	$1,648,902	$420,540
1988-89†	$1,837,937	$434,436
1989-90	$1,876,665	$441,327
1990-91	$1,546,078	$542,377
1991-92	$1,401,976	$546,770

[1] The sources of information available for different years varied. Receipts for years designated with an "*" are for sales of timber, poles and posts. This information is taken from IDNR annual reports for the Division of Forestry. Receipts for years with a "†" designation include timber, poles, posts and nursery, UPS and publication sales. Annual reports for these years could not be found in publically available inventories (e.g., the Indiana Government Documents library). Consequently, this information was supplied by the IDNR from Division of Forestry revenue summary documentation supplied to Koontz during his research (Koontz, 1997).

[2] This is an approximation. Camping fees were illegible in the document I was using.

[3] Timber sales alone for this year were about $750,000 (IDNR Division of Forestry, 1986:20)

[4] Timber sales alone for this year were about $1,000,000 (IDNR Division of Forestry, 1987:12)

Figure 4-1: Diagrammatic Representation of Six Silviculture Systems
(Source: Kimmins, 1992:60)

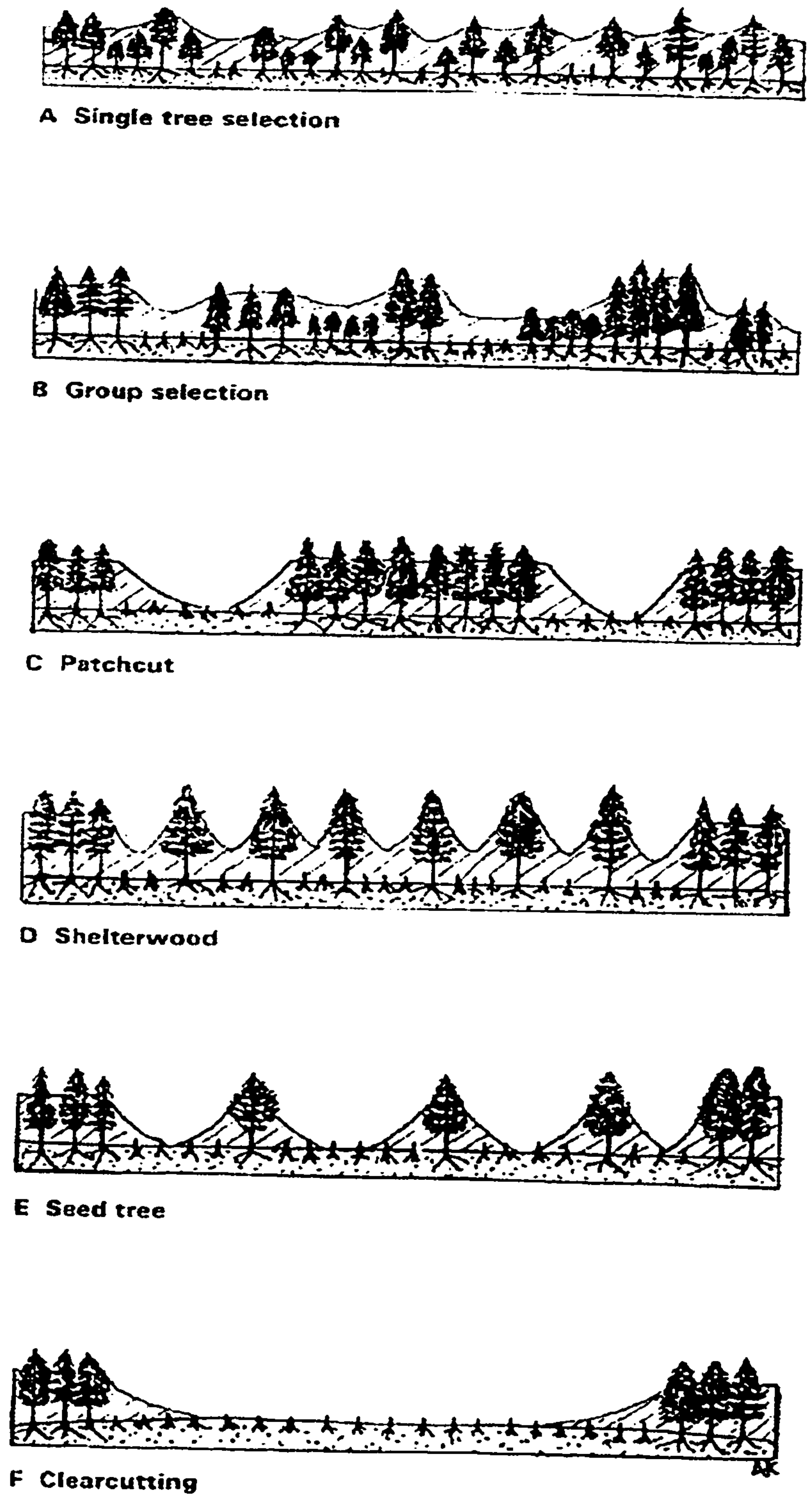


Figure 4-2 Summary of Variables Affecting Activity Choice

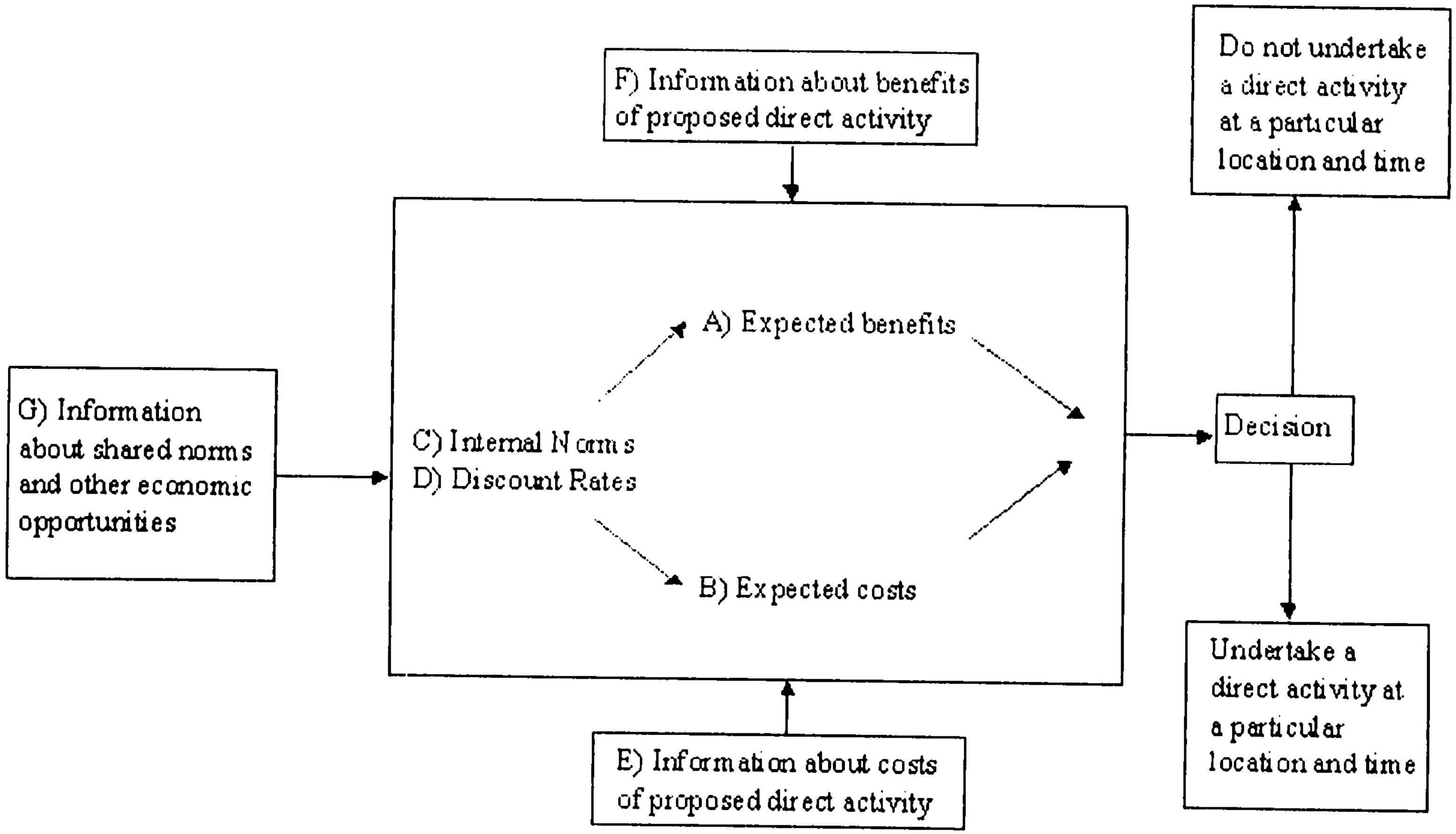


Figure 4-3: Current Boundaries of the Hoosier National Forest and Yellowwood State Forest in the Indiana 9 County Satellite Image Overlap Region

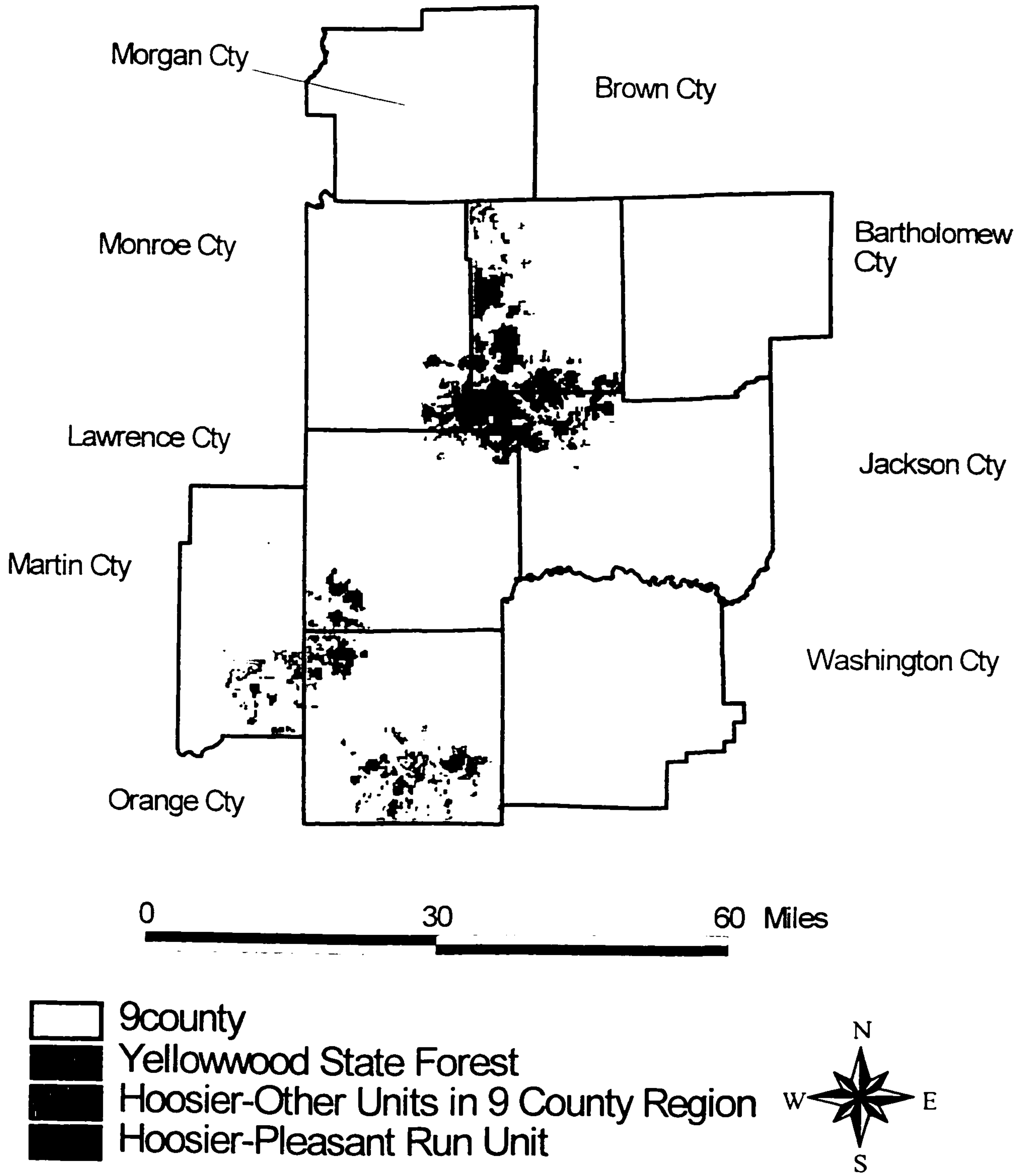


Figure 4-4: Percent of Sheet Erosion and Gullying in Indiana Counties Based on Information Collected by the Soil Conservation Service, US Department of Agriculture, 1935

(Adapted from Sieber and Munson, 1992: 86)

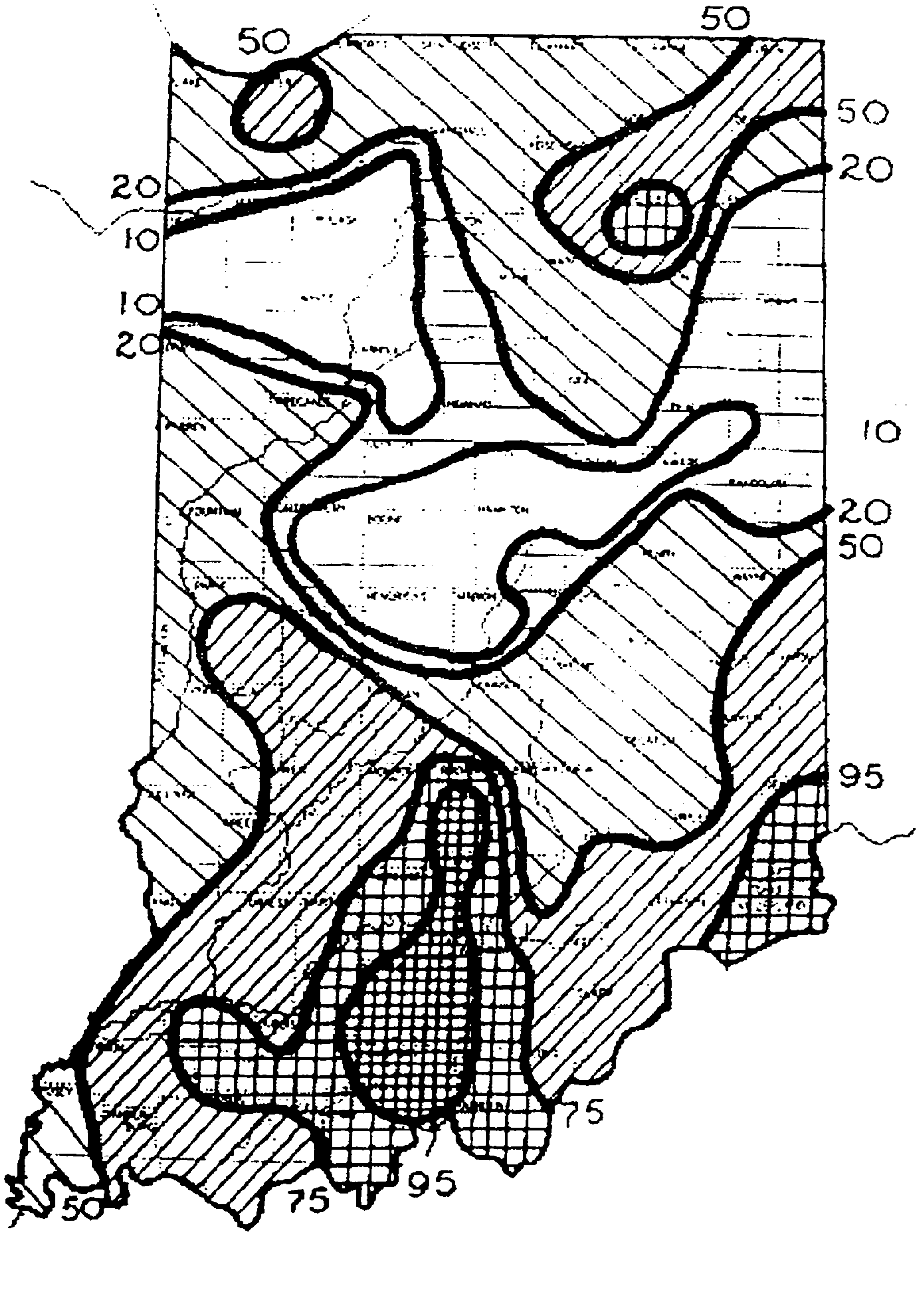


Figure 4-5: The Hoosier National Forest Pleasant Run Unit Pre-1985 Institutional Landscape
(Adapted from 1985 Final Environmental Impact Statement. Hoosier National Forest. Alternative 1 Map)

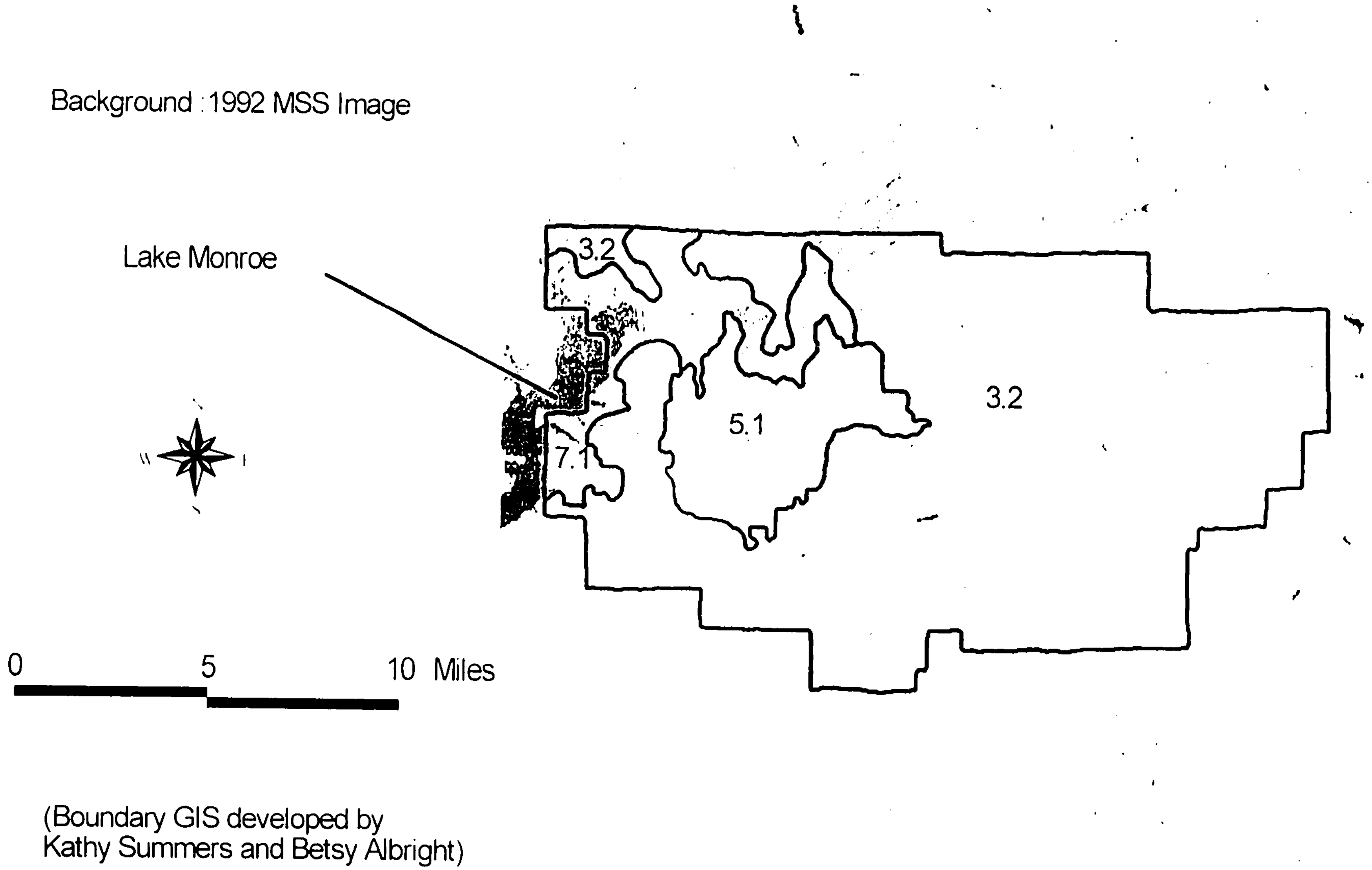
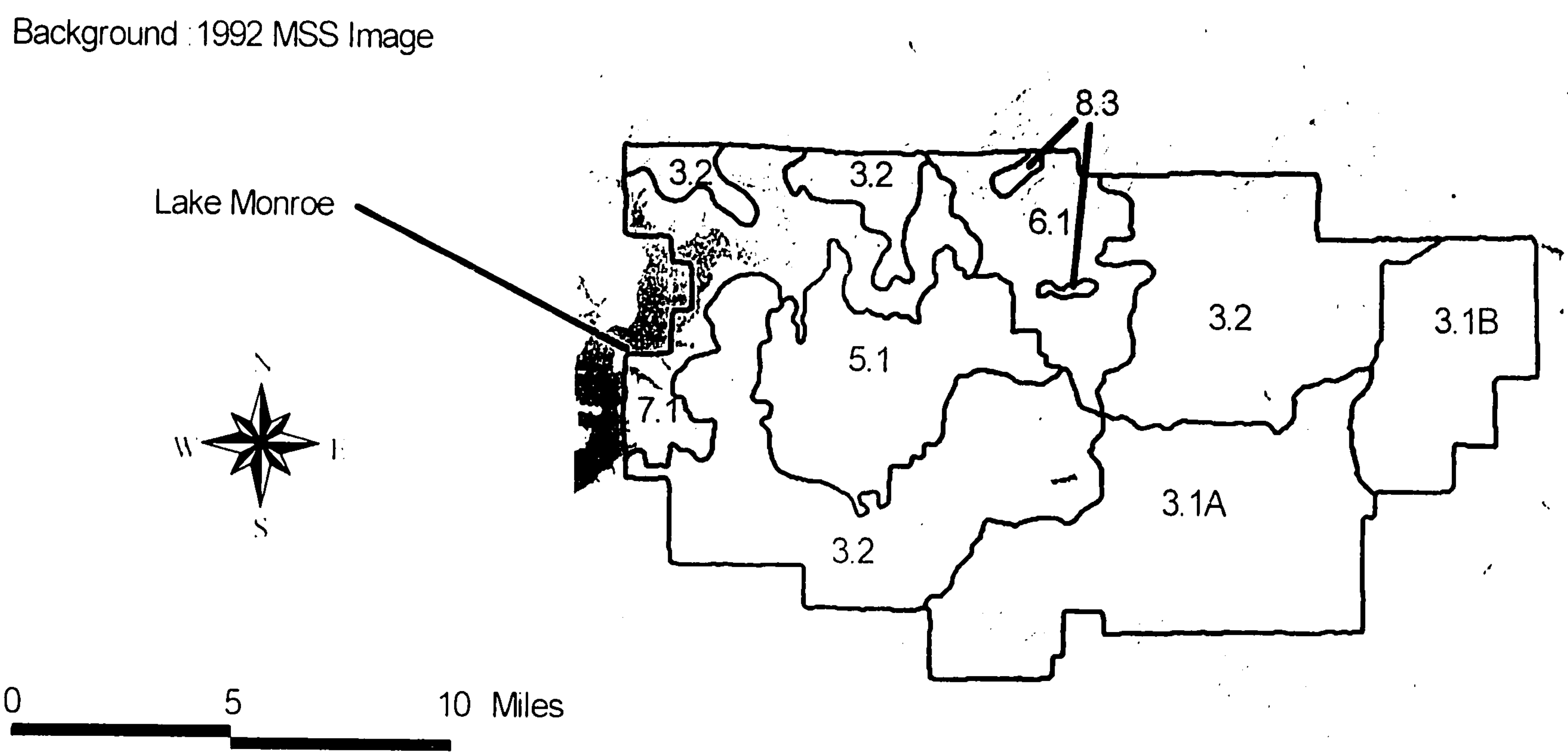
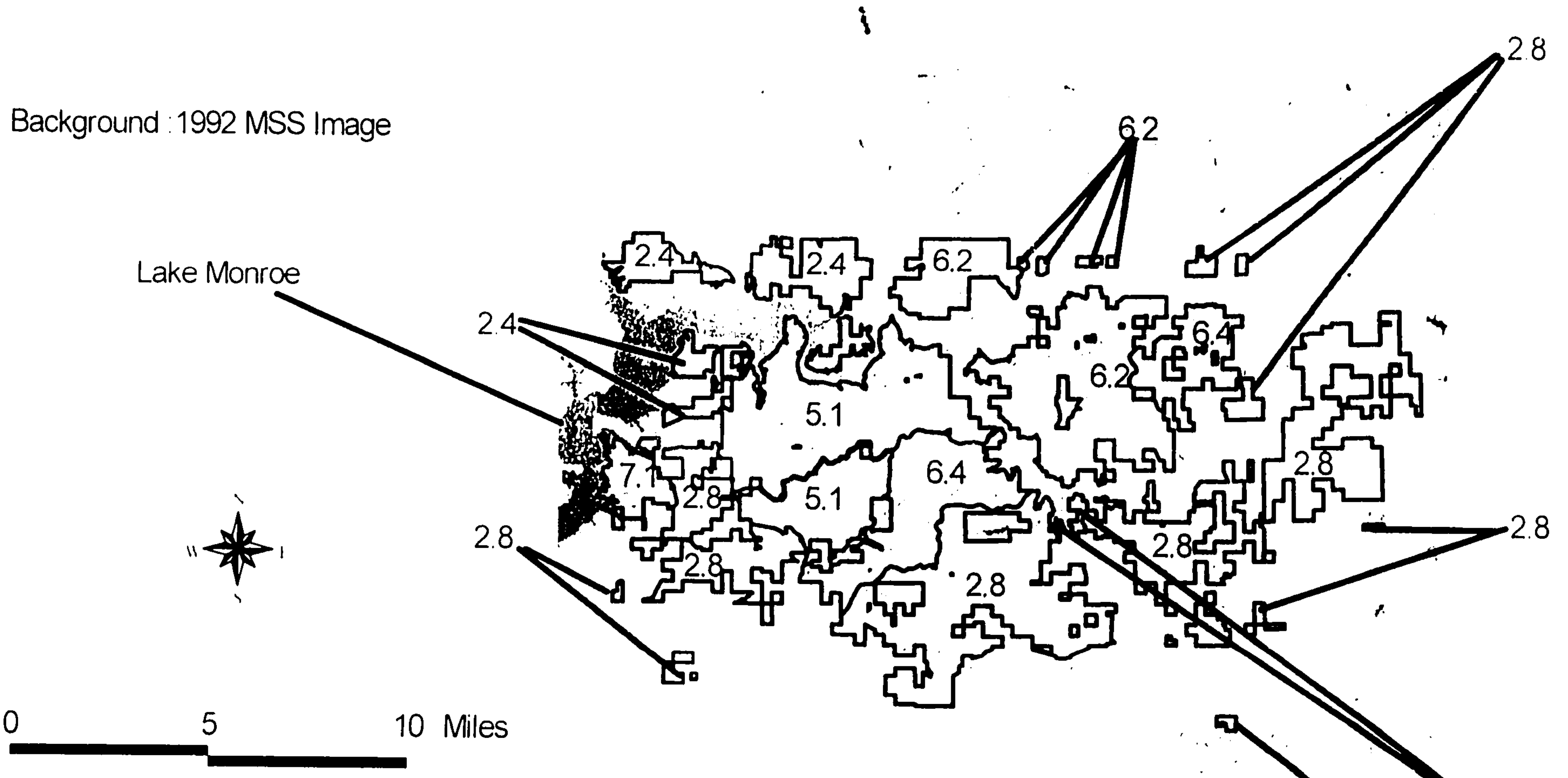


Figure 4-6:
The Hoosier National Forest Pleasant Run Unit 1985 Institutional Landscape
(Adapted from 1985 Land and Resource Management Plan. Hoosier National Forest)



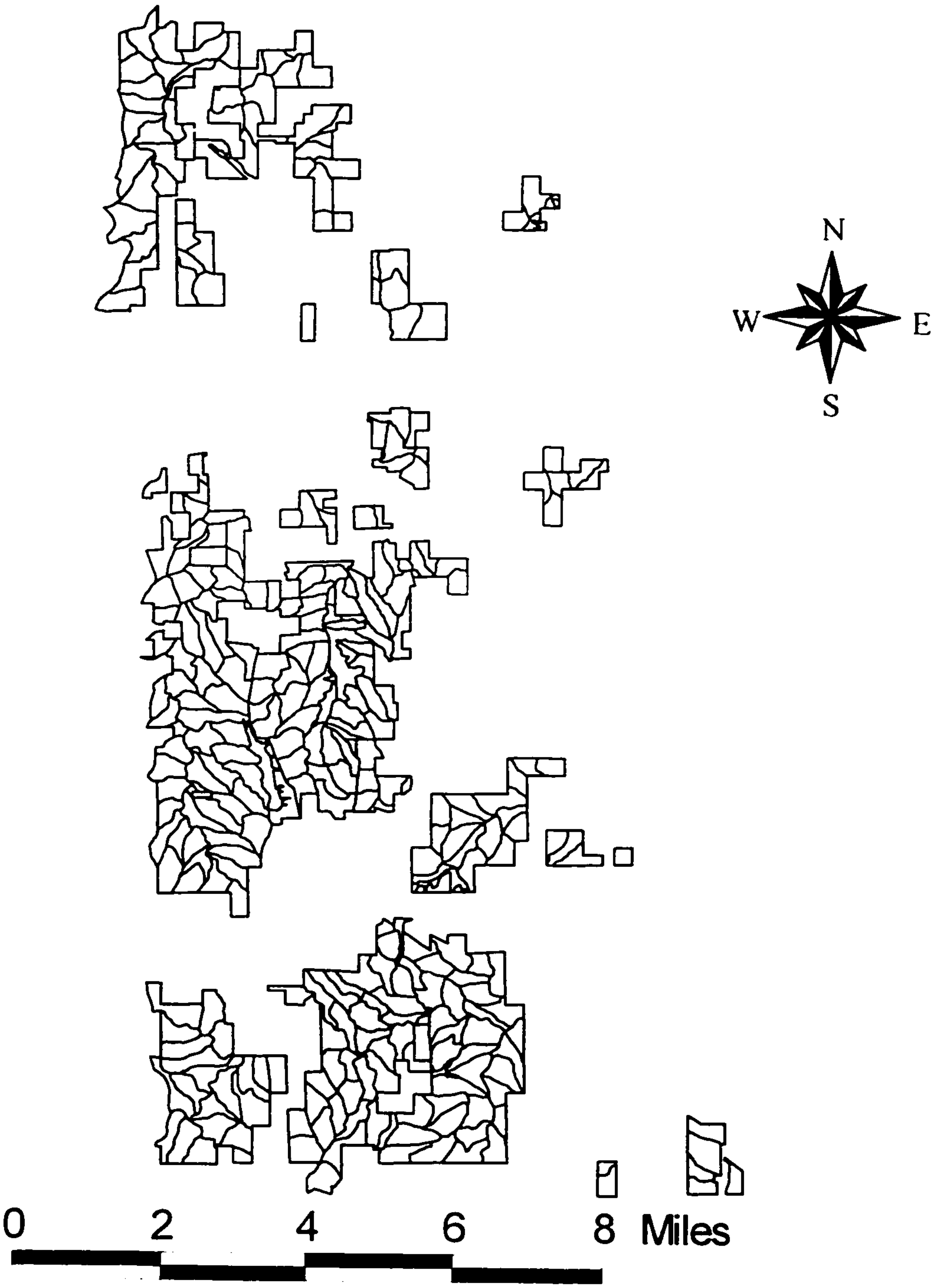
(Boundary GIS developed by
Kathy Summers and Betsy Albright)

Figure 4-7: The Hoosier National Forest Pleasant Run Unit 1991 Institutional Landscape
(Adapted from 1991 Land and Resource Management Plan Amendment. Hoosier National Forest)



(Boundary GIS provided by Professor
J.C. Randolph, Director Midwest Center for
the National Institute of Global Environmental Change)

Figure 4-8: The Institutional Landscape at Yellowwood State Forest -- Tract Boundaries



Chapter 5

THE PROMISE OF SPECTRAL MIXTURE ANALYSIS FOR STUDYING THE HUMAN DIMENSIONS OF ENVIRONMENTAL CHANGE

Chapter one argues that one of the major difficulties in understanding the human dimensions of environmental change is the fact that in many locations little or no longitudinal data exist on the dependent variable--the condition of the physical landscape. It is expensive and time consuming, for example, to travel to the field and sufficiently sample a forest. It is even more expensive to then return at a later point in time and sample it again.

It is in part due to these problems that the interest in the use of remote sensing techniques to quantify landscape condition and change has increased in recent years. Remote sensing is defined by Campbell (1996:5) as "the practice of deriving information about the earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth's surface." Our ability to derive information about the earth's surface using air or space snapshots of reflected visible or nonvisible light provides a potentially cheap and efficient method to inventory and quantify areas of the earth.

A history of remote sensing will not be summarized here (see Campbell, 1996:4-8 for a brief summary). But while remote sensing as a mode of landscape inventory has been around for decades, it is only more recently that social science researchers are beginning to tap into its potential as a research tool for studying the human dimensions of environmental change. Over the last decade or so, scholars in geology, geography, anthropology and other fields have been able to acquire a single image of an area of the earth, process it using high-performance mainframes and workstations and then classify the land cover at this one point in time. However, the advances made over the last five or so years in GIS and image processing on workstation and desktop computer platforms, have made it an opportune time to combine remote sensing and other research techniques developed by social scientists.

There are, however, many types of remotely sensed images available, produced using by a variety of different systems and sensors. One of the first major decisions a researcher make if he or she decides to utilize remotely sensed images is which type of image to utilize (Wilkie and Finn, 1996). Important to this decision, are factors related to scale and image product

Scale Issues and the Use of Multispectral Satellite Images for Land Cover Change Detection

The term scale has various meanings depending on the discipline.[1] For example, scale, as used by a cartographer, refers to the size of a map feature and its relationship to the entity it represents in reality. When we see a map scale of 1:50,000 we know that one unit on the map is proportional to 50,000 of those units on the ground. To many others in the social and physical sciences, scale refers to the quantitative or analytic dimensions used to measure and study objects or processes (Gibson, Ostrom and Ahn, 1997: 3; Lillesand and Kiefer, 1994). Whether referring to time or space,[2] scale typically is defined by two attributes: "extent" and "resolution." A third term, "grain," is also often associated with scale

Extent

Extent refers to the size or area of a particular study. Spatial extent involves the definition of a geographic area and temporal extent involves the specification of a particular length of time (Turner, *et al.* 1989)

Resolution

Resolution describes the precision to which data related to a phenomenon of interest are measured (Gibson, Ostrom and Ahn, 1997). Note that this definition applies to the data being used to study a particular phenomenon. The phrase "image resolution" has been shown to have various meanings (Forshaw *et al.*, 1983). In regard to satellite images, there are several resolution types: spatial, spectral, radiometric and temporal. [3]

Spatial resolution is probably the concept most commonly understood. Spatial resolution of satellite images is often described in terms of the pixel size or the "instantaneous field of view" (IFOV) of the satellite sensor that detects brightness of radiation being emitted from the ground. The IFOV is determined by the size of the detector, and the altitude and optics of the sensor used to measure the brightness of radiation emitted from the earth's surface (Wilkie and Finn, 1996). For example, France's SPOT satellite system has a spatial resolution of approximately 20 square meters, the U.S. Landsat Thematic Mapper's sensor has a spatial resolution of about 30 square meters, and the U.S. Landsat Multispectral Scanner sensor has a spatial resolution of approximately 79 x 56 meters (Campbell, 1996).

Spectral resolution is defined as the "width across the electromagnetic spectrum that the remote sensing instrument is detecting." (Verbyla, 1995: 6). Satellite platform sensors vary in terms of spectral resolution. For example, France's SPOT high-resolution visible sensor working in multispectral mode senses three spectral regions: the green visible (.50-.59 μm),[4] the red visible (.61-.68 μm) and a portion of the near infrared region (.79-.89 μm) (Campbell, 1996). Landsat's MSS and TM sensors, on the other hand collect spectral information along four and seven regions of the electromagnetic spectrum, respectively (See Table 5-1).

*** Table 5-1 about here ***

Radiometric resolution describes how precise a satellite's sensor is to differences in radiation reflected or emitted from ground features (Wilkie and Finn, 1996: 47). Holding spatial and spectral resolution constant, an increase in the radiometric resolution of a sensor will likely increase the detection and identification of landscape features. Sensor technologies have improved in their radiometric resolution over time, in part because of the improvements in digital storage of data. For example, the earlier Landsat Multispectral Scanner (MSS) sensor has a seven bit system of representation and can therefore store radiation values measured by numbers between 0 and 127. The later Landsat Thematic Mapper (TM) technology utilizes an eight bit resolution and can store radiation measurements quantified by numbers between 0 and 255. Landsat TM then has improved radiometric resolution over Landsat MSS. It is obvious that an improvement of radiometric resolution will improve our ability to discriminate between landscape features on an image.

Temporal resolution describes how often a satellite obtains images of a particular location (Wilkie and Finn, 1996: 48). Different remote sensing systems have varying orbital return schedules. Traditional aerial photograph inventories, could be considered having coarse temporal resolution. In southern Indiana, for example, overflights have been conducted approximately once every ten years. Land inventory satellites such as Landsat could be classified as having moderate temporal resolution because they return to the same location as frequently as sixteen days (Campbell, 1996). Weather satellites such as the NOAA AVHRR have a higher temporal resolution, for they revisit the same location twice a day (Lillesand and Kiefer, 1994). The choice of an appropriate temporal resolution is absolutely critical in regard to how images might be used to inform analysis. One may wish to control for time-varying features such as vegetation response to change of season, or one may wish to capitalize on this change to identify particular land cover features.[5]

Grain

The term grain is often used as a synonym of resolution as defined above (see for example, Lillesand and Kiefer, 1994: 633; Turner *et al.*, 1989; Cleveland, *et al.* 1995).[6] This, in part, comes from fields such as photography that references the grain size or resolution of film (Drury, 1990). In some literature, however, there is a rival definition. Grain, can be used to describe the spatial or temporal extent of the *phenomenon*--not the data--one wishes to study. In the context of space, some landscape ecologists utilize the phrase "the grain size of a landscape," referring to the size (e.g., fine, medium and coarse) of the landscape elements present (Forman and Godron, 1986: 216). A "landscape element" is defined as a basic and relatively homogeneous ecological unit, whether of natural or human origin, on the landscape (Ibid., p. 595).

Perhaps an example will help to clarify this meaning of the term grain as it is applied by this group of landscape ecologists. Figure 5-1 (A) shows a photograph of the Yellowwood Lake region in Brown county Indiana taken at a mapping scale of roughly 1:50,000. Viewed at this analytic scale, this landscape could be considered coarse, for the landscape elements, largely forest and agriculture patches, exhibit diameters of a few kilometers or more. The aerial photograph of clear-cut patches surrounding Mt. Baker in Figure 5-1 (B) provides an example of a medium grained landscape. These human-induced patches average perhaps a few hectares in area. The natural distribution of trees and shrubs in the photograph of a dry savanna in Figure 5-1 (C) exhibit a fine landscape grain. Each patch of trees or shrubs surrounded by the bare ring of soil around it encompass smaller areas that can be measured in smaller numbers of meters.

*** Figure 5-1 about here ***

It should be clear from the three examples in Figure 5-1 that the definition of a landscape's spatial grain is directly related to the scale (i.e., extent and resolution) one decides to utilize for analysis (Pielou, 1974). For example, as stated earlier, if an analysis of the full landscape at the scale as it is shown in Figure 5-1 (A) would be conducted, one would conclude that the landscape elements are coarsely grained. But if one "zoomed in" to a finer scale and studied in greater detail changes in individual trees within the forest canopy just adjacent to Yellowwood Lake in the center of the photo, one begins to study a much finer phenomenon and would conclude that this component of the landscape, at this scale, exhibits a finer landscape grain.

Up until now the discussion on grain has focused entirely in the context of space. This is in part because most people refer to grain in this context. I define "temporal grain" as the length of time a particular landscape phenomenon can *continue to be observed* at a particular scale. For example, the clear cut patches in Figure 5-1 (B) may remain detectable in aerial photographs taken at the same spatial scale for the length of time it takes forest vegetation to regenerate to the growth stage just prior to the cutting. Or, alternatively, if the successionary vegetation that fills in the patches is sufficiently different from the surrounding vegetation, the pattern of disturbance may remain observable over a much longer period of time. To a large degree then, the task of identifying the temporal grain of forest management phenomena is an empirical question. In sum, this study utilizes the following definitions:

Extent:	*The size of a particular study, measured in terms of area for the spatial dimension and length of time for the temporal dimension*
Resolution:	*The precision to which data related to the phenomenon of interest is measured.*
Grain:	*The spatial and/or temporal extent within which the phenomenon of interest is readily observable.*

The above distinction between resolution and grain is vital when one begins to consider the use of temporal sets of satellite images to study the phenomenon of human decision-making and activities on the physical landscape. The choice of an appropriate image data set for analysis turns critically to the grain size of the phenomenon of interest, the choice of the satellite platform system to utilize and issues related to the resolution of the image data it provides (Wilkie and Finn, 1996).

The Utility of Landsat Multispectral Scanner (MSS) for the Study of Human Dimensions of Environmental Change

The Landsat ("land satellite") system, designed in the 1960s and first launched in the early 1970s, was specifically developed for the observation of the Earth's terrestrial surface (Campbell, 1996 158). Table 5-1 provides a summary of the Landsat system. Six Landsat satellites or "platforms" have been launched, beginning in 1972. Landsat 5 continues to be operational, working well beyond its intended life span. Two primary sensor instruments exist on these platforms the Multispectral Scanner (MSS) and the Thematic Mapper (TM) MSS instruments were employed on Landsat platforms 1 through 5 TM instruments were first included on Landsat 4, remain on Landsat 5 and an enhanced version (ETM) will be launched on Landsat 7 Table 5-1 also provides a summary of these instruments

This study utilizes the older MSS technology. TM images provide more information content and are more readily used. But at this point in time, the use of MSS technology is vital. There are several justifications for the use of MSS imagery in studies on the human dimensions of environmental change, and many of these reasons are directly associated with the discussion of scale issues above.

First, both the MSS and TM data archives cover a broad spatial extent. Each individual image taken by Landsat MSS sensors covers a "footprint" on the Earth of approximately 185 square kilometers. Further, since Landsat's inception in 1972, all of the earth's terrestrial surface between 81° N and 81° S latitude has been subject to image acquisition (Campbell, 1996: 162)

Second, the Landsat data archive covers a relatively long temporal extent (twenty-five years). While this may be short in terms of the history of humanity, twenty-five years covers a long enough temporal range to capture much of the human induced change that has occurred in forested landscapes. This is especially true in locations where land cover change is rapidly occurring, such as in developing countries where forests are being rapidly converted to agriculture. Whether this time span adequately captures forest management activities in other areas of the earth, such as in state and national deciduous forests in the U.S., is an empirical question this research hopes to address.

Third, the MSS instrument provides a reasonably high degree of spectral resolution when compared to other remote sensing platforms such as aerial photographs, France's SPOT or India's IRS satellites. MSS has four sensors or "bands," each sensitive to a different portion of the electromagnetic spectrum. As Table 5-1 shows, MSS band 1 responds to light at the visible green wavelengths (0.5-0.6 micrometers or μm), band 2 responds to light in the visible red portion of the spectrum (0.6-0.7 μm), and both band 3 and band 4 respond to different portions of near-infrared wavelengths (0.7-0.8 μm and 0.8-1.1 μm respectively). While other technologies such as Landsat TM, NOAA's AVHRR or hyperspectral instruments such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) provide even better spectral resolution than MSS (Verbyla, 1995; Campbell, 1996), the data MSS provides is probably adequate for addressing many of the questions being asked in the human dimensions of global change research program. Many of the activities humans undertake on the physical landscape is dramatic, involving vegetation-to-soil or soil-to-vegetation type conversions. These types of changes provide dramatic contrast in land cover reflectance spectra (see Figure 5-2) that can be adequately captured with the spectral resolution MSS provides

*** Figure 5-2 about here ***

Fourth, the temporal sampling of the Landsat MSS system is relatively high. Location coverage repetition frequency was approximately eighteen days for Landsat 1,2 and 3 and is sixteen days for Landsat platforms 4 and 5. This revisit frequency is probably adequate for addressing many of the more important human-induced processes related to landscape change. While cloud cover may inhibit some of the images acquired, for any given location within these latitudes, there is likely a large temporal set of images available for sampling. Figure 5-3 provides an example. The diagram depicts the available Landsat MSS and TM images with twenty percent cloud cover or less for the area of this study in south-central Indiana. This figure provides a good example of just how many usable images may have been acquired over the current life span of the Landsat system for any given location.[7]

*** Figure 5-3 about here ***

Open Questions Related to the Utility of MSS for Human Dimensions of Environmental Change Studies

As evidenced by the previous discussion, there are ample reasons to consider the use of Landsat MSS toward studying human decision-making and land-cover change. However, there is one significant limitation: the relatively poor spatial resolution provided.

Other satellite platforms described earlier, such as Landsat TM and SPOT, provide relatively fine spatial resolution with 28.5 x 28.5 meter and 10 x 10 meter spatial resolutions respectively (Campbell, 1996). A pixel in an MSS image is coarser, capturing roughly a 79 meter x 56 meter area on the ground or roughly 1 U S football field. This spatial resolution, may limit the amount of information related to human activities that MSS images can provide. To a large degree the utility of MSS depends on the grain (e.g., size of spatial extent and degree of spectral contrast) of disturbance as a result human activities that are occurring in a region.

Wilkie and Finn are cognizant of this issue. They state:

> It is very important to emphasize that for the spatial resolution of a remote sensing system to be appropriate to the question, the feature of interest must not only be detectable by the sensor. It must also be identifiable and analyzable by the researcher. Detectability is the ability of a remote sensing system to record the presence or absence of a feature on the landscape. A feature can be detected even if it is smaller than the theoretical spatial resolution of the sensor (e.g., a high-contrast object such as a concrete road or a wheat field). Recognizability is the ability of the human interpreter to identify (put a name to) a feature detected by sensor systems. A feature may be detected by the sensor but may not be recognizable (e.g., narrow straight lines in an image may be roads, railways or canals) (1996: 41).

Building on work by Jensen (1986), these authors provide a rule of thumb related to research of landscape and specifically forestry related phenomenon:

> For a unique feature to be both detected and identified successfully it should be made up of no fewer than 3-5 pure pixels--that is, pixels composed solely of the unique reflectance from the feature of interest (with no edge effects). For many agriculture and forestry applications this translates to feature sizes being greater than 20-50 IFOVs or pixels (Jensen, 1986:29)... (p. 43)

Consequently, Wilkie and Finn (1996: 91) provide an equation that they use to estimate the spatial resolution required to observe forest logging. Their equation is reproduced below in more general terms:

$$\text{Spatial resolution required} = \sqrt{\frac{\text{Minimum area of phenomenon of interest } (m^2)}{\text{Minimum number of pixels required for recognizability}}} \quad (Eq\ 5.1)$$

Wilkie and Finn use an example of forest cutting to show how this equation can be applied. They assume that the area of a forest cut (the numerator in Eq. 5.1) could be as small as 2 hectares or 20,000 m^2. They use Jensen's (1986 29) minimum recommendation of 20 pixels for the recognizability (the denominator in Equation 5.1). Their conclusion: images with at least 30 meter pixel resolution is required to capture this phenomenon.

Based on Wilkie and Finn's calculations, small areas (2 hectares or less) of forest disturbance will not be adequately detected and recognized using MSS images. The spatial resolution of 79 meters x 56 meters is too coarse for humans to recognize small forest disturbances in the images. Their recommendation brings into question the utility of MSS as a tool for understanding human induced landscape change and forest disturbance that is small in spatial extent. Their advice should be taken seriously: their arguments are well thought out and are based on what appears to be substantial practical forest monitoring experience.

We therefore face a tradeoff. It is clear that for these types of questions, images with a higher spatial resolution are favorable, such as ones created by Landsat TM or SPOT. However, while Landsat TM and SPOT images have much better spatial resolution, they lack as much temporal extent as MSS, covering 18 and 12 years respectively.[8] Since forest disturbance phenomena occur often at spatial extent longer than 18 years, it is important for the analyst to maximize the temporal range of available multispectral satellite imagery. From this perspective, the use of MSS is absolutely critical for it extends back a full 25 years to 1972.[9] Put succinctly, the dilemma is this:

> *Do we give up on the possibility of using MSS to study human dimensions of environmental change in instances where we think the majority of human disturbance occurs at smaller spatial extent? Or do we try to find other analytic methods that perhaps improve MSS detectability and recognizability?*

Traditional Analysis Techniques and the Promise Of Spectral Mixture Techniques

It is important to note that Wilkie and Finn's recommendations are based to a large degree on the ability of humans to recognize features in an image. I believe they make this assertion based on underlying assumptions they make in regard to image analysis. The analytic techniques they describe in their book are largely based on the traditional image classification techniques and the use of channel-to-channel ratios.

However, the use of another technique developed by geologists and planetary scientists called "spectral mixture analysis" or SMA (Adams *et al.*, 1986, 1993, Smith *et al.*, 1990a, b) has the potential to make MSS based analyses more applicable to the study of fine spatial scale forest disturbance phenomena. It holds promise in that it allows a more detailed analysis at the pixel level than other more traditional image analysis techniques and perhaps diminishes the need for the role of human recognizability in analysis. To support this reasoning, this section will provide a very brief summary of the more traditional image analysis techniques and then will describe SMA and how it might be used to improve the utility of MSS for human dimensions related studies.

Traditional Image Analysis Techniques

Standard or traditional image analysis techniques have been developed since the early 1970s. Image analysis in this context refers to methods for displaying and interpreting band-to-band variations. Generally, the traditional analytic tools include single band analysis, color compositing, band-to-band and color composite ratioing, principal component analysis and classification. These methods are used widely in analyzing Landsat produced images (Adams, *et al.*, 1993).

Single band analysis involves the process of reviewing individual bands of an image separately, usually using a grey scale display. Color compositing techniques superimpose three bands together and display each band of information using blue, green and red. For instance, for MSS, the visible green band is often displayed using blue, the visible red band is displayed in green, and the second infrared band is displayed in red. This simulates what would be generated if the image was taken using color-infrared film (Lillesand and Kiefer, 1994). One limitation in using color composites is that only three channels of information can be displayed at one time (Adams *et al.*, 1993).

Band-to-band ratioing is another analysis technique using multispectral satellite images for the study of land cover. For example, vegetation indices are one group of popular band-to-band ratios. Vegetation chlorophyll is known to absorb visible red light and leaf mesophyll tissue reflects near infrared light (Campbell, 1996). As the amount of vegetation increases within the boundaries of a pixel, reflection in the visible red decreases while reflection in the near infrared increases (Hall, 1994). Vegetation indices take advantage of these properties. There are a number of types of indices that have been applied, but they all involve mathematical ratios or differences of the digital values of different spectral bands to produce a single value for each pixel. This value provides a measure of the degree of vegetation biomass existing within the pixel boundary (Campbell, 1996)

One of the most popular vegetation index is referred to as the "normalized difference vegetation index" or NDVI. The NDVI value for each pixel is calculated via the following equation

$$\text{NDVI} = \frac{(\text{Near infrared - Visible red})}{(\text{Near infrared + Visible red})} \qquad \text{(Eq 5 2)}$$

Pixels with high vegetation biomass and leaf area index[10] will result in high NDVI values (Hall, 1994)

One of the reasons why NDVI and other such ratios are found to be useful is that they provide a physical measure of the vegetation content within a pixel area. By taking advantage of the spectral response of vegetation, these indices allow us to develop a measure of one component of each pixel. There have been a variety of studies that have utilized ratios as part of their analysis (see for example, Tucker, *et al.* 1985; Cohen, 1991; Sader and Wynne, 1992). One of the limitations of ratios is that they do not take advantage of all the available information contained in multispectral images. They usually utilize two bands only, unless a ratio is generated using color composites, where, in those rare cases data from three bands are employed (Adams, *et al.*, 1993).

Principal component analysis (PCA) is another technique traditionally used to remove interband correlation that typically exist within multispectral image data. PCA identifies linear combinations of the original band data of an image to produce component images representing variation in the pixel data (Campbell, 1996). Often the purpose of PCA is to "compress" all the information contained in a n-band image data "cube" into a new image data cube with fewer than n bands or components. These component images are then used in place of the original band data (Lillesand and Kiefer, 1994). This sometimes helps to preprocess the data to remove noise such as image striping (Idrissi, 1997). As this is being written, some scholars are investigating the use of the higher components (e.g., components 5 and higher in TM images) to identify patterns in human activity (Turner, 1998). It is thought that the first few components capture variation that is a result of natural factors, while the latter components capture more of the patterns that can be tied to human activity. One benefit of PCA is that it utilizes all the data provided in a multispectral image.

Classification methods are one of the most common analytic techniques applied to multispectral images (Adams, *et al.* 1995). This becomes quite apparent when one traverses through the remote sensing literature developed throughout the 1970s, 80s and 90s. Most remote sensing related texts devote significant effort (sometimes the majority of the discussion of analysis) to image classification procedures (see for example, Lillesand and Kiefer, 1994, Verbyla, 1995; Campbell, 1996; Wilkie and Finn, 1996). These methods work to assign individual pixels of a multispectral image to categories (Drury, 1990). The goal of these types of analyses is to replace a visual analysis of continuous image data with quantitative techniques for identification of land cover classes within the image (Lillesand and Kiefer, 1994).

Two types of classification procedures are popular and work in conjunction with one another. Unsupervised classification procedures group or cluster the multispectral values of the image into distinct classes (e.g., water, soil and vegetation classes) and produce a new raster[11] map displaying the class locations within the image (Hall, 1994). This output matrix has the same spatial resolution as the image from which it was produced. Supervised classification involves the use of ground inventories to guide or "train" the computer to assign appropriate clusters of data to certain ground-truthed data classes (Ibid.). Various strategies (e.g., parallelpiped, maximum likelihood) have been employed to utilize training data to produce classifications of those pixels not assigned to training areas (Campbell, 1996). Many important human dimensions of environmental change studies have utilized image classification as their dominant image analysis method (see for example, Westman *et al.*, 1989, Sader, 1995, Moran, *et al.* 1994, Brondizio, *et al.*, 1994, Lee and Marsh, 1995 and there are many, many more.) Others have combined their analytic strategy by employing both classification and band-to-band ratios (e.g., Lee and Marsh, 1995, Wolter, *et al.*, 1995).[12]

One great advantage of classification methods is that they utilize all the data provided by multispectral images. However, there are two important limitations of classification procedures. First, only one land cover category or class can be assigned to each pixel or cell in the image matrix. In other words, one 79 x 56 meter pixel in an MSS scene can only be assigned to one class or land cover category. Yet in most instances, the land will be comprised of multiple types of landcover in many settings. Second, classifications employed are usually scene dependent. Typically they are based on digital numbers and have not been "restored" to at earth reflectance (see the "image restoration" discussion below). Non-surface sources of variability remain in the image values and influence the way the data are classified. Figure 5-4 provides a summary of the types of variability that reside in digital number data. Further, any expansion of geographic coverage within one individual scene may reveal a new land cover type which would then alter classification groupings. For these reasons, classifications, based on satellite digital numbers without image restoration, cannot be applied to other geographic locations.[13]

*** 5-4 about here ***

Spectral Mixture Analysis

Efforts have been made to address these limitations in classification techniques (e.g., Jackson, 1983, Conel and Alley, 1984) Spectral mixture analysis (SMA), also referred to as "linear unmixing," is one promising technique that has developed from efforts of earth and planetary scientists (see for example, Singer, 1979, Kornder and Carpenter, 1984; Adams and Adams, 1984; Adams, *et al.*, 1986, Smith *et al.*, 1990a; 1990b and Ustin, Smith and Adams, 1993)

General land cover types (e.g., soil, water, vegetation) have been shown to exhibit different patterns of reflectance over the wavelengths along the electromagnetic spectrum (often referred to as "spectral signatures"). Figure 5-2 shows the typical look, referred to as "stick spectra," of these general land cover features. Some physical landscapes may have very distinct land cover types. For example, a desert landscape may have sand as one major land cover type and clumps of vegetation as the other major land cover component. In instances such as these, pixel data may exhibit more "pure" forms of spectral responses, and classification is an appropriate analytic technique.

In reality, however, land cover surfaces are often composed of a variety of mixes of materials and the distinction between them (especially from space) is not so cut and dry When a sensor observes a pixel comprised of mixed types of surfaces the reflectance spectra produced will not match pure spectra like the examples shown in Figure 5-2. Rather, the pixel spectral response will exhibit a shape over the electromagnetic wavelength that is some sort of mixture of various land cover spectra (Campbell, 1996). For example, a pixel composed of both soil and vegetation will have a spectral response that looks like some combination of the general soil and vegetation stick spectra shown in Figure 5-2.

The objective of SMA is to identify primary spectral contributions within each pixel (Adams, *et al.*, 1993: 149). It provides a means for determining relative abundances of land cover materials present in any given pixel based on the spectral characteristic of the material (ENVI, 1996).

SMA involves two main steps. The first step is to define a set of spectra for selected land cover material often referred to as "endmembers." These can be identified using either (1) libraries of known spectra collected with a spectrometer in the field or in a laboratory; (2) libraries of known spectra from previous SMA studies; or (3) spectrally pure or "extreme" pixels identified within the images being analyzed. This study will follow option 3, since it is, to my knowledge, the first of its kind done in south central Indiana and no libraries of field collected endmember spectra exist that can be utilized and no spectrometer is available to collect spectra in the field. The third option involves the application of a "pixel purity index" algorithm that searches an image for the most spectrally pure pixels (ENVI, 1996). Pixel endmembers are selected by testing whether its spectral signature can be described as a mixture of pixel spectra previously analyzed, or whether it is itself another end member (Adams, Smith and Gillespie, 1993). A simple hypothetical illustration is provided in the diagram in Figure 5-5.

*** Figure 5-5 about here ***

Figure 5-5 (A) provides a graphic of the spectra for vegetation, soil and shade. The vertical grey bars represent the electromagnetic wavelength regions of two bands, 1 and 2. Figure 5-5 (B) plots the values of various pixels of an image in 2-dimensional space for band 1 and 2 using "Xs." Pixels comprised of entirely one component, vegetation, soil or shade, would plot at the corners of the triangle represented in Figure 5-5 (B). Pixel purity functions help to identify pixels in an image that lay at the extremes of the triangle of pixel points, in n-dimensional space. The number of endmembers chosen must be one less than the number of bands available in the multispectral image (ENVI, 1996). For MSS images, with four bands, three endmembers can be identified. For TM images, six endmembers can be identified if all seven TM bands are utilized. Once endmembers are identified, their spectra can be presented in a form similar to Figure 5-5 (A) and can be stored in a spectral library for use in this and future studies.[14]

The second step in SMA is to estimate, for each pixel, the abundance of each endmember contained within it by applying a linear mixing equation (Adams, Smith and Gillespie, 1993; ENVI, 1998). The general form of this equation, in matrix form, is as follows: where,

$$R^{[m \times 1]} = EM^{[m \times n]} * X^{[n \times 1]} + e^{[m \times 1]} \qquad (Eq\ 5.3)$$

R	Original image calibrated to surface reflectance values
EM	Endmember spectra matrix
X	Vector of unknown abundances or fractions
m	Number of image bands used
n	Number of endmembers used (must be m-1 or less)
e	Root mean-squared (RMS) error in the fit of the model. It represents the sum of the squared residuals over all m bands.

This linear mixing equation is used to convert the existing image spectra values for each pixel into endmember fraction matrices. One fraction matrix or image is produced for each endmember along with the RMS error matrix. This procedure requires that the fraction values produced in matrix X to be positive and sum to unity (Ibid.). These fraction images can be created for each time point in a temporal set of satellite images all based on the same endmember spectra.

To date, very few studies have applied SMA toward questions related to the human dimensions of environmental change. But it has great potential over the more traditional image analysis techniques for several reasons.

First, like classification and principle component analysis, SMA utilizes the entire "data cube" of a multispectral image. All the information contained within the image are employed in the analysis.

Second, unlike traditional methods such as classification, SMA is scene independent. In SMA, particular end members can be identified from image data, field or lab inventories or from endmember fraction libraries (Bateson and Curtiss, 1996). For this reason, time series or multiple geographic location SMA fraction coverages–important products for analyzing environmental change--are more readily comparable than are the products from classification techniques based on digital numbers.

Third, endmember fraction coverages represent physical properties of the landscape based on reflectance. Classification maps often represent human language artifacts--e.g., a "forest," or a "pasture"--that may have different meanings to different people and are not directly tied to physical measures of reflectance.[15] Two pastures may be labeled the same but may be comprised of varying vegetation types and may exhibit very different spectral qualities. Analyses conducted using endmembers, being founded on spectral qualities and not human artifacts, can therefore be more easily applied to other geographic areas.

Fourth, endmember fraction images are more appropriate for analysis of physical landscapes exhibiting a high degree of continuous land cover, such as densely forested areas.[16] While classification is quite useful in physical landscapes with discrete land forms, it may not be as easily applied to land cover that is less easily distinguishable.

Finally and perhaps most importantly, fifth, SMA provides the spectral data in terms of end member fraction coverages and not in a single pixel classification, hence allowing a more detailed analysis of pixel contents (Adams *et al.* 1993). Because of this, some refer to the linear mixing approach as a "sub-pixel" analysis (ENVI, 1998). From this we can get a better idea of what mixture of land cover features comprise any individual pixel. The same amount of data are used in SMA and in classification techniques, but the employment of SMA endmembers and the production of endmember percentage images allows for a more detailed analysis of pixel contents. This is especially important when using coarse images such as Landsat MSS and this is largely why this chapter is entitled "the promise of spectral mixture analysis. " It may allow us to discern more information from MSS imagery than can be done using more traditional techniques such as classification.

The Importance of "Image Restoration" Procedures

Given these justifications for SMA and given concepts related to SMA have been around for over at least 10 years (e.g., see Adams and Adams, 1984), the reader may ask the question, why hasn't SMA been more widely utilized? There are two answers to this question.

SMA requires the identification of pure reflectance spectra from the image itself or using spectra libraries (Adams, *et al.*, 1993). The individual band "digital numbers" or DNs provided in the raw images received from U.S. repositories such as EROS and EOSAT do not represent at-earth reflectance that can be immediately utilized. They contain the non-surface variation exhibited in Figure 5-4. Nearly 15 years ago, Robinove recognized and nicely summarized the problem which still is prevalent today:

> Landsat digital images are commonly analyzed by using the digital numbers for each pixel recorded on computer-compatible magnetic tape. Although this procedure may be satisfactory when only a single, internally consistent image is used, the procedure may produce incorrect results if more than one image is used for analysis as in mosaics or temporal overlays. The digital numbers... vary depending on the calibration of the multispectral scanner in each satellite at a given time, the sun angle, the state of the atmosphere, the slope and aspect of the terrain, and surface cover (1982: 781).

In order to develop reflectance spectra of endmembers from the image itself, or utilize an endmember reference from a library, the image must have sensor, illumination and atmospheric variation removed from the DNs. In other words, the DNs must be converted to surface reflectance (Green, Schweik and Hanson, 1998). As Robinove suggests, this conversion–what is sometimes referred to as "image restoration" (Jensen, 1996; Green, Schweik and Hanson, 1998)–is vital for any SMA temporal or spatio-temporal comparison.[17]

The first answer to the question "why has SMA not been used" is because it is technically difficult[18] to undertake full image restoration. Green, Schweik, and Hanson (1998) provide an overview of the image restoration process. When image comparisons are to be made, after preprocessing steps,[19] three main restoration processes should be undertaken: radiometric calibration, atmospheric correction and radiometric rectification. Some of these steps related to image restoration are fairly well documented, such as atmospheric correction (Chavez, 1988) and radiometric rectification[20] (Hall *et al.*, 1991).

Radiometric calibration involves converting of image DNs to radiance values and radiance to at-satellite reflectance[21] (Robinove, 1982; Markham and Barker, 1986; Hill, 1991). While the information on how to conduct radiometric calibration is available, the literature is scattered and not readily available to the environmental change research community (Green, Schweik and Hanson, 1998). The procedures required differ by satellite platform and by sensor. A literature review of major remote sensing journals revealed that over the past 10 years only a small proportion of researchers actually convert DNs to surface reflectance (Ibid, 1998). Classification of one time point or even multiple time points can be conducted without conversion to reflectance by applying radiometric rectification procedures (Hall, *et al.*, 1991), as long as the researcher has no interest in applying the same classification to another geographic area. The procedure presented by

Hall, *et al.* (1991) normalizes images from multiple time points to a reference or base image. Because of this ability to normalize images taken at different times but of the same location, the technical difficulties in converting DNs to at-satellite reflectance appears to be considered by many to be not worth the effort. This decision to leave images in DN data space means that SMA cannot even be considered as an analysis option on these products.

The second answer to the question is simpler. SMA computer programs are largely unavailable. SMA itself is a fairly complicated process (see Adams, *et al.*, 1993) and is largely prohibitive unless software is written to allow such an analysis to be undertaken. At the point of this writing, surprisingly, SMA is still not available as part of the general analysis tools available in even the most prominent image processing packages.

Let me now elaborate on the methodological question "M4" presented in Chapter 1 and Chapter 3. Important questions related to the utility of MSS imagery to the study of human dimensions of environmental change are:

> *M4 Part 1) How well does the <u>resolution</u> provided by temporal sets of MSS imagery capture the <u>grain</u> of various forest management activities in South Central Indiana using SMA as an analysis tool?*
>
> *M4 Part 2) What are the spectral responses to direct forest management activities of varying spatial extent?*
>
> *M4 Part 3) Which can and cannot be observed using SMA of MSS images?*

Chapter 6 is devoted to answering these questions, by applying GIS and SMA to analyze areas of known human activities in one particular deciduous forest in south-central Indiana.

Chapter 5 Endnotes

1. Gibson, Ostrom and Ahn (1997) provide a useful discussion of scale as it relates to disciplines within the social sciences. Their analysis helps to clarify how various disciplines define and use the concept of scale and attempts to develop a cross-disciplinary language by suggesting a set of common or unifying terms and definitions.

2. In the social sciences, scale is also used to describe quantitative and analytic dimensions of any phenomenon of interest. See Gibson, Ostrom and Ahn (1997) for more details

3. The discussion here will only be a cursory discussion of these four types of resolution. For a more complete discussion, the reader is encouraged to read Chapter 3 of Wilkie and Finn (1996).

4. It is assumed that the reader has some familiarity with the regions along the electromagnetic spectrum. For a relatively good overview, see Campbell (1996: 22-29).

5. For example, it might be helpful to analyze a set of satellite images by season of one year, to help in identifying land undergoing seasonal agriculture activities.

6. Other scholars keep this definition of grain, but have altered slightly the meaning of the term resolution. Turner and colleagues (1989: 246), for example, define [spatial] grain as "[t]he finest level of spatial resolution possible with a given data set," in other words, the data sets precision. Resolution, in their usage, takes on a slightly different meaning: it refers to the "precision of measurement: grain size, if spatial." Using this definition in the context of space, one could aggregate or combine neighboring image pixels and work at a less precise degree of spatial resolution even though the spatial grain of the image data set remains the size of an individual pixel.

7. A Landsat "location" is often referenced by a Path and Row number. Figure 5-3 provides a list of images available for Path 21, Row 33 of Landsat 4 and 5, and Path 23, Row 33 or Landsat 1,2 and 3. Landsat acquires images following an orbital design referred to as the "Worldwide Reference System" or WRS (Campbell, 1996: 172). This reference system defines the nominal center points of Landsat images via a coordinate system where roughly north to south orbital swaths are referred to as "Paths" and horizontal east-west reference lines are referred to as "Rows." The orbital height from the earth changed when Landsat 4 was launched thus leading to a modification of the WRS system between Landsats 1-3 and Landsats 4-5 platforms. This system provides a useful method to index Landsat images.

8. Landsat TM technology was first launched in July, 1982 therefore providing a current temporal extent of 18 years. SPOT-1 was launched in February 1986 thus providing a current temporal extent of 12 years (Lillesand and Kiefer, 1994). While these time periods may be long enough to study many human-environment phenomena (e.g., rapid land cover

change in tropical forests) these temporal extent are probably too short to adequately capture some of the forest disturbance cycles in countries like the United States where forest vegetation tends to grow more slowly

9 As shown in Table 5-1, Landsat TM was first used in the Landsat 4 platform, launched in 1982 If one decided to use Landsat TM imagery only for analysis, one would be essentially leaving out 10 years of multispectral data collected by Landsat 1-3. Similarly, if one decided to utilize data from another satellite platform, such as France's SPOT or India's IRS, one would have similar reductions in temporal extent The first SPOT satellite was launched on February 21, 1986 so to date it has amassed about 11 years of image data Similarly, India's first multispectral satellite, IRS-1A was launched in 1988 This is not to say these satellite image inventories are not important--the absolutely are--but they simply do not cover the broad temporal extent that the Landsat MSS sensors have

10. Leaf area index (LAI) is defined as a "unit-less measure of the ratio of the surface area of all leaves to the ground area" (Wilkie and Finn, 1996 266)

11 "Raster" is the name given to one form of geographic information system that associates spatial data in the form of cells within a matrix One band of a satellite image can be considered a raster data structure for each digital number is associated with one cell (e g., a 30 x 30 meter pixel in the case of Landsat TM) in the image matrix.

12 One difficulty in using these indices is that they are influenced by many components not associated with plant leaf (e.g , soil background and sensor differences) (Campbell, 1996). These ratios are also very sensitive to the particular atmospheric conditions of an image primarily because the atmosphere can cause light in the visible portions of the spectrum to scatter. Atmospheric calibration is advised to remove the effects of atmospheric scattering (Teillet and Fedosejevs, 1995, Green, Schweik and Hanson, 1998) Others emphasize the importance of restoring the image from "raw" digital values to at surface reflectance before calculating these ratios to minimize sensor drift problems and other factors (e.g., Price, 1987) Unfortunately, the procedures required to remove many of the variance caused by non-vegetation effects is difficult and not readily accessible to many scholars using remotely sensed images. Many analyses may have employed vegetation ratios without removing these effects which may have led to false conclusions (Green, Schweik and Hanson, 1998).

13. A literature review described in Green, Schweik and Hanson (1998) discovered that classification was the dominant type of image analysis and very few authors converted image digital numbers to physical measures of at-earth reflectance This means that their classification schemes cannot be readily transferred and applied to studies at other locations.

14 The ability to store chosen endmembers in a library is extremely valuable for the human dimensions of global change research program. This means that we can begin to store spectra of particular material on the ground, and apply the same endmembers for

analysis in other regions if applicable. For studies comparing two similar but geographically separated locations, this will be extremely useful. It is very difficult to conduct this type of study using classification techniques (see Green, Schweik and Hansen, 1998)

15. I am indebted to Glen Green for this insight.

16. This is especially important for this study, for the forested areas in Indiana that are being analyzed are heavily vegetated areas.

17. This is also true as the global change research community begins to compare more traditional image products (e.g., classifications) across time or geographic space (Duggin and Robinove, 1990; Davis, *et al.* 1991). See Green, Schweik and Hanson (1998) for more discussion on these research strategies.

18. Walsh (1989) suggests that the greatest source of uncertainty in time series analysis using satellite images may be a result of the data tranformations that occur during image restoration processing. This is because of the significant and difficult technical processes that are required to convert DNs to surface reflectance

19. Image preprocessing involves the removal of pixel to pixel variability not associated with atmospheric or surface phenomena. It involves the conversion of images from CD to the appropriate image processing software format, removing any artifactual noise from the image such as line drop outs and line striping, and geometric rectification.

20. Radiometric rectification is a procedure which essentially normalizes sets of time series image data to some base image. This ensures that time series images are directly comparable. For classification based analyses, time series images in DN space can be directly compared as long as this radiometric rectification process has been conducted (Green, Schweik and Hanson, 1998).

21. At-satellite reflectance describes the ratio of light received by the sensor from the entire Earth-atmosphere system over the solar irradiance at Earth-Sun distances. These values contain the effects of the atmosphere such as scattering and absorption.

Table 5-1: Landsat Satellite Instrument Specifications

(Adapted from Campbell, 1996)

	Satellite Platform						
Instrument	Landsat 1: Launched 7/23/72; Out of Service 1/6/78	Landsat 2: Launched 1/22/75; Out of service 2/25/82	Landsat 3: Launched 3/5/78; Out of service 3/31/83	Landsat 4: Launched 7/16/82 Operational, "standby"	Landsat 5 Launched 3/1/84; Operational	Landsat 6 (Failed to reach orbit)	Landsat 7 (Expected launch date. Mid 1999
MSS	✔	✔	✔	✔	✔	--	
TM				✔	✔	--	✔ ("Enhanced TM +"

Summary of Instrument Sensors

Instrument	Band	Spectral Sensitivity	Resolution
MSS	1	0.5-0.6 μm (green)	79 x 56 m
MSS	2	0.6-0.7 μm (red)	79 x 56 m
MSS	3	0.7-0.8 μm (near infrared)	79 x 56 m
MSS	4[1]	0.8-1.1 μm (near infrared)	79 x 56 m
TM	1	0.45-0.52 μm (blue-green)	28.5 x28.5 m
TM	2	0.52-0.60 μm (green)	28.5 x 28.5 m
TM	3	0.63-0.69 μm (red)	28.5 x 28.5 m
TM	4	0.76-0.90 μm (near infrared)	28.5 x 28.5 m
TM	5	1.55-1.75 μm (mid infrared)	28.5 x 28.5 m
TM	6	10.4-12.5 μm (far infrared)	120 x 120 m
TM	7	2.08-2.35 μm (mid infrared)	28.5 x 28.5 m

[1] In Landsat platforms 1, 2 and 3, these were referred to as Bands 4-7.

Figure 5-1: Examples of Fine, Medium and Coarsely Grained Landscapes

(A) <u>Coarsely grained landscape</u>
This 1939 aerial photograph of the Yellowwood Lake region of Indiana might be considered a coarsely grained landscape for the patches of landscape elements (e.g., forest cover and agriculture plots) average a few kilometers in diameter.

(B) <u>Medium grained landscape</u>
This aerial photograph of clear-cut patches surrounding Mt. Baker in Washington State is considered a medium grained landscape, with landscape elements averaging a few hectares in area.
(Adapted from Forman and Godron, 1986, 205)

(C) <u>Finely grained landscape</u>
This is a aerial photograph of woody plants in a dry savanna provides an example of what Forman and Godron consider a finely grained landscape. Each tree or shrub patch encompasses an area of only few meters.
(Adapted from Forman and Godron, 1986, 195)

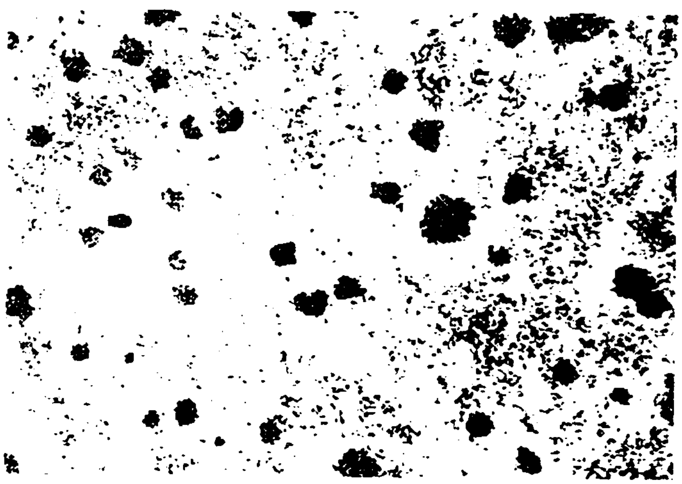


Figure 5-2: Typical Continuous Spectral Reflectance Curves for Vegetation, Soil and Water
(Adapted from Richards, 1986)

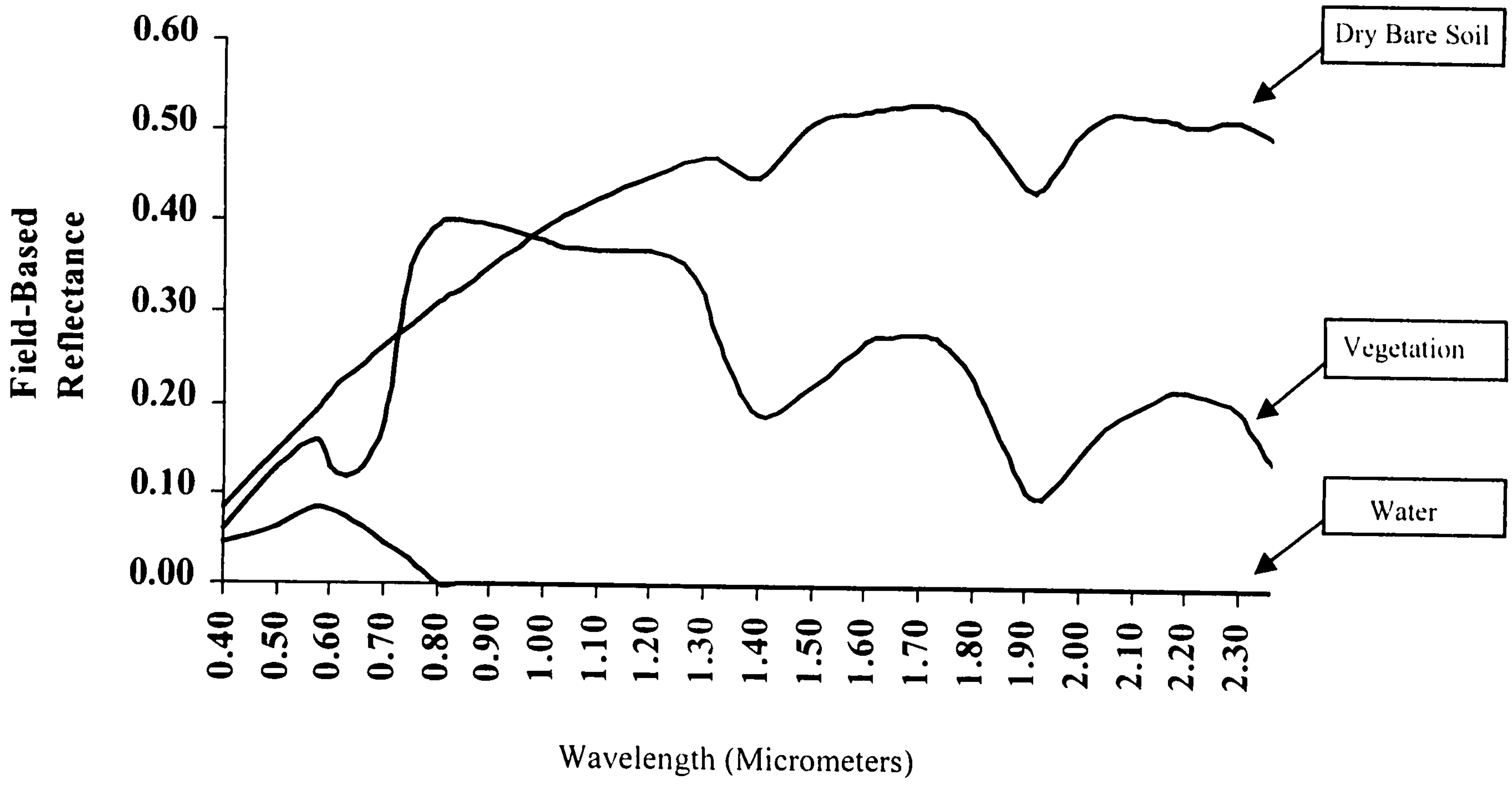
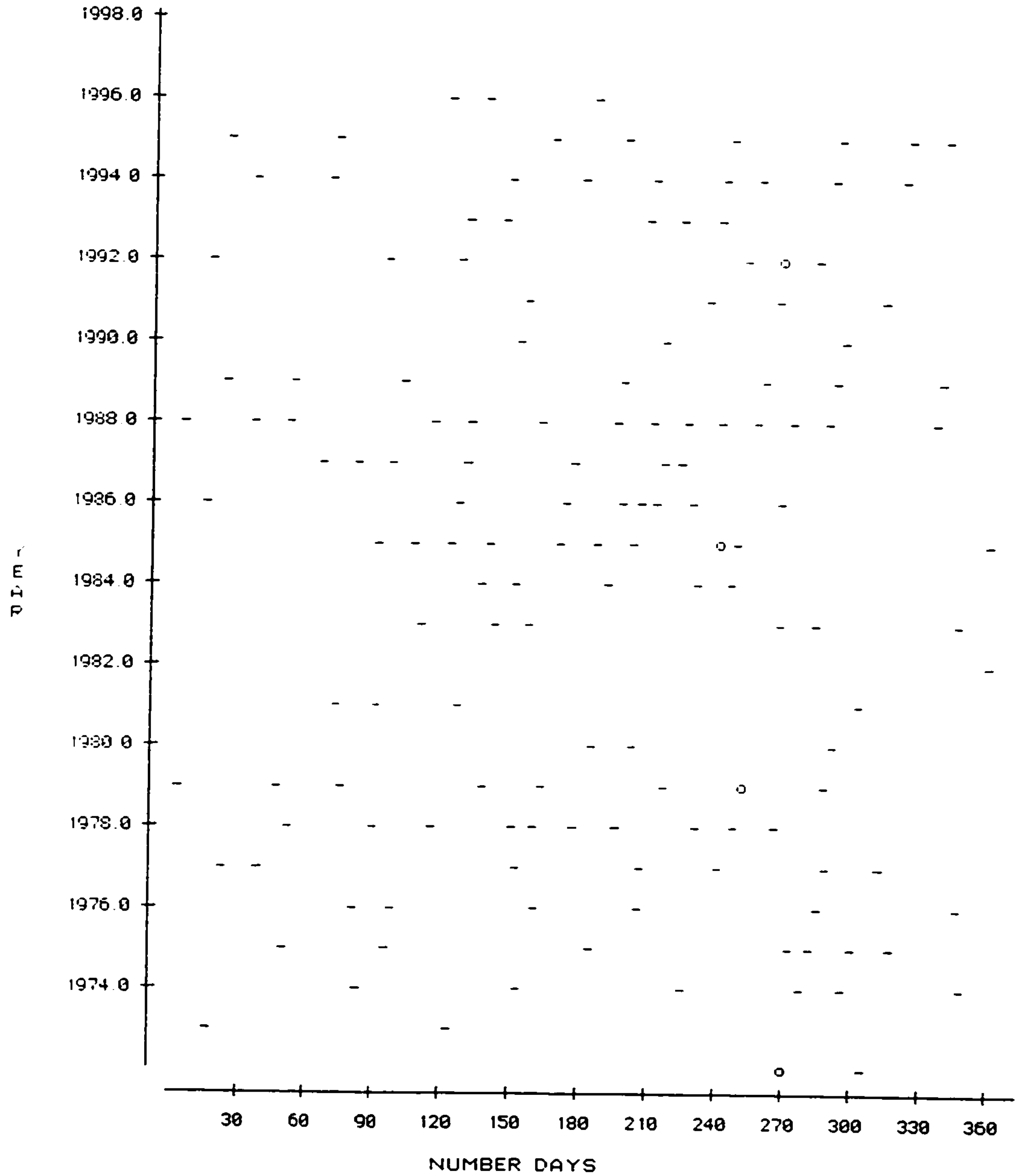


Figure 5-3. Diagram of Available Landsat MSS and TM images Available for the South Central Indiana Study Location (WRS 1, Path 23, Row 33; WRS 2, Path 21, Row 33)



Note: Circles represent images selected for use in this study:
9/30/1972, 9/12/1979, 9/01/1985 and 9/28/1992

Figure 5-4: Non-Surface Sources of Variability in Landsat Images

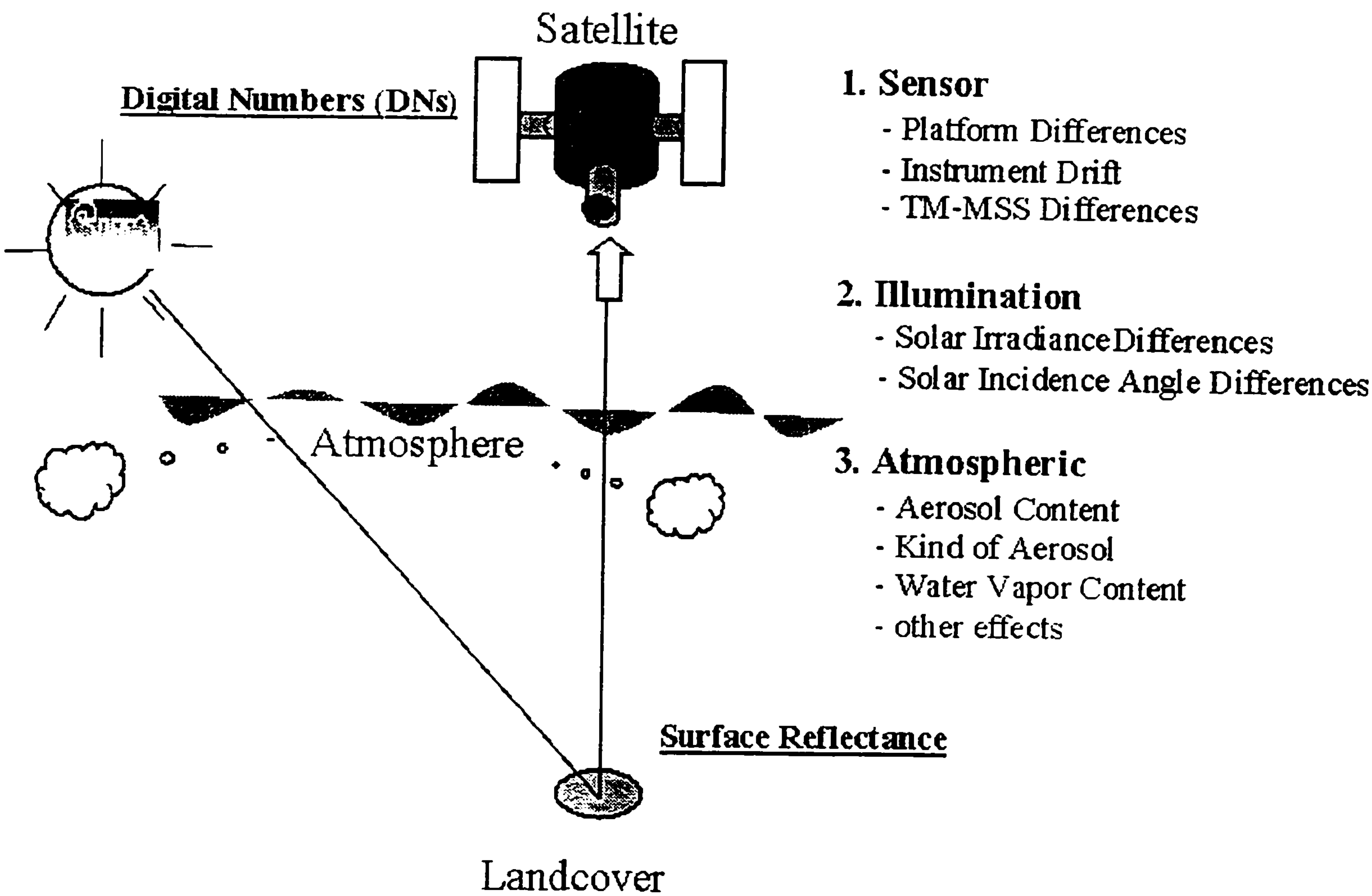
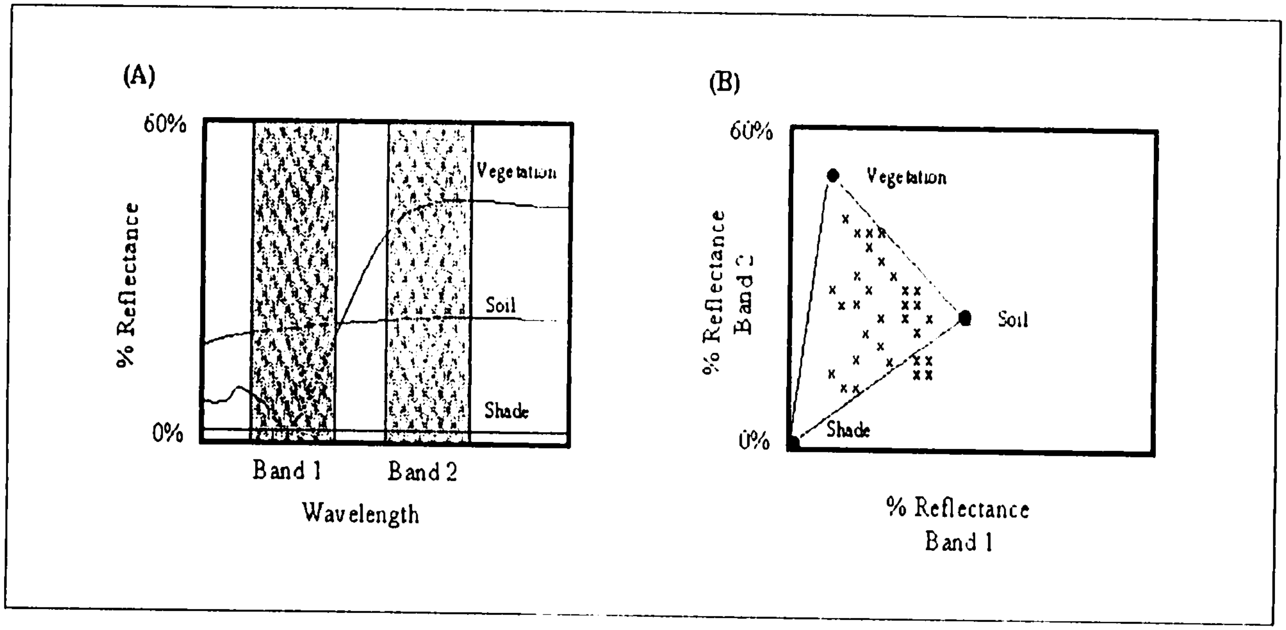


Figure 5-5: Diagram Representing Hypothetical Image Data for Spectral Mixture Analysis (Adapted from Adams, Smith and Gillespie, 1993:152)



Chapter 6

TESTING THE SENSITIVITY OF LANDSAT MSS AND SPECTRAL MIXTURE ANALYSIS TO STUDY HUMAN-INDUCED CHANGE IN DECIDUOUS FORESTS

This chapter addresses the questions posed at the end of Chapter 5. It investigates whether the Landsat MSS platform with its four-band spectral resolution and its eighty meters squared[1] pixel size is capable of identifying human-induced changes in deciduous forests. In addition, in the process, it hopes to begin the establishment of a "spectral library" of land cover types for the South-Central Indiana region and the midwest United States in general.

Accomplishing this task requires a study forest where a very good historical understanding of the human activities exists for the 1972-1992 time period. Indiana's Morgan-Monroe state forest, managed by the Indiana Division of Natural Resources, is such a forest. In addition to having excellent historical records of human activity, this forest is representative of other forests in the region.

This chapter is organized in the following manner. First, I provide a critical theoretical discussion on the properties of light reflectance in leaves and forest canopies. This foundation is crucial if we are to investigate how the disturbance which results from human activities may alter the reflectance of forested landscapes. Second, I summarize methods used to prepare the satellite images and create the GIS required for spectral mixture change analysis. Third, I present the results. Findings about the sensitivity of the MSS time series to various human induced are described. The chapter concludes with a summary of findings, methodological lessons learned and goals for Chapter 7.

Leaf Morphology and Forest Canopy Reflectance

Simply put, change that occurs in multispectral satellite images of forested areas will be one of two general types. It will be either: (1) conversion of vegetated areas to some non vegetative state (e.g., soil, development) or vice versa; or (2) conversion in vegetation composition and/or structure. Spectrally, the former is easier to identify. Soil (and other non vegetative matter) has distinctly different spectra over the electromagnetic spectrum compared to vegetation (refer back to Chapter 5, Figure 5-2). This makes studies of dramatic spatial change (e.g., forest to permanently developed areas across a large region) an easier task that is often conducted with classification analysis. Detecting change in the latter, vegetation composition and structure, however, is often less dramatic and can be more difficult to detect. In public forests in Indiana, it is this second class of forest change that tends to occur more often.

The major factors that affect reflectance from forest canopy areas are leaf area and leaf optical properties that are a product of leaf morphology (Green, 1996). It is well understood that chlorophyll in the palisade layer of leaves absorbs red and blue light for use in photosynthesis (Figure 5-2). Less green visible (.55 μm) is absorbed by plants thereby making them look green to the human eye (Figure 6-1).

*** Figure 6-1 about here ***

The vegetation spectra example shown in Figure 5-2 reveals an even more significant increase in reflectance starting from the near-infrared (.7 μm) through the mid-infrared (1.9μm). This reflectance, is a response not of the chlorophyll molecules but rather by the deeper internal structure of a leaf's spongy mesophyll tissue (Knipling, 1970; Campbell, 1996).[2] In studies of Oak-Hickory forest stands in Missouri (Green, *et al.*, 1985; Green and Arvidson, 1986; Green, 1988; Green, 1996), distinctly high near-infrared reflectance values were found to be associated with vegetation residing in xeric environments—areas with soils that exhibit low water detention capabilities. Alternatively, these studies report that forest vegetation in more mesic (wet) environments tend to have lower values in near-infrared reflectance. Green (1996) attributes the higher infrared reflectance in xeric vegetation to qualities of leaf internal structure that are an adaptation to environmental conditions. Xeromorphic leaves differ from mesomorphic ones in that they have a thicker outer layer or cuticle (Kramer and Kozolowski, 1979; Spurr and Barnes, 1993) and a higher ratio of internal to external surface (Kramer and Kozlowski, 1960) (Figure 6-1).

If xeromorphic and mesomorphic leaf structures are so important in determining vegetation infrared reflectance, how might this be related to the impact human activities have on forests? To answer this question we must consider factors that influence a plant's access to water: topography; climate and weather; and plant age.

Topographic location is, largely, a "naturally" produced factor. While humans have been known to make significant modifications to the topography when they set their minds to it, in general we can still assume the topographic component of the physical landscape is still largely a product of nature. Water availability in any given topographic setting is higher in valley areas where water tends to flow. In this region of the United States, stand areas exhibiting larger bottom land and northeast facing slopes will have higher water content within their soils than tracts located on ridge tops or south-west facing slopes (Huebner, Randolph and Parker, 1995) Green and colleagues (Green, *et al.* 1985; Green and Arvidson, 1986; Green, 1988, 1998) have discovered the tendency of midwestern deciduous forest canopies to reveal a high infrared reflectance in xeric environments and lower infrared reflectance in mesic environments.

Another naturally created phenomenon, the climate, determines the type of vegetation that grows in a particular region. Consider the distinction between tropical and temperate deciduous forests. Further, fluctuating weather patterns from year to year or within a year is also thought to be a determining factor in leaf structure development. Nordhausen (1912) finds that leaves, exposed to wet conditions later in their life cycle, remain xeromorphic if water availability was low during bud creation. Leaf morphology is thought to be determined at the bud stage (Daubenmire, 1974) The likelihood is high, then, that the reflectance of leaves particular canopy late in the season (e.g., September) may therefore be a function of water availability in the spring or even in the previous year (Green, 1998).

The age of a tree may also affect the internal structure of its leaves. Most water consumed by trees is absorbed by the root system (Spurr and Barnes, 1992). Older trees, with well-developed root systems will have more access to water retained in the soil than young trees with less developed root systems. Younger trees, having less developed root systems will have less access to available water in the soil. Moreover, young trees residing in open areas such as windthrows or timber cutting areas, will have more exposure to direct sunlight, thus taking on a more xeric leaf structure than similar species growing in shade (Spurr and Barnes, 1992).

Remote sensing studies have discovered relationships between near-infrared reflectance and stages of forest regrowth (Sader, *et al.*, 1989; Fiorella and Ripple, 1993, Mausel *et al.*, 1993; Moran, Brondizio and Mausel, 1994; Moran, *et al.*, 1994; Brondizio, *et al.*, 1996; Steininger, 1996). In a study on Amazonian vegetation, Mausel *et al.* (1993) discovered that initial secondary growth shows lower near-infrared reflectance in initial years, but higher near-infrared in intermediate successionary stands. They find that advanced secondary succession shows a lower near infrared compared to the intermediate successionary stage but still higher than in the initial fallow period. In another study on the Amazonian forests, Steininger (1996) reports a significant increase in near-infrared reflectance in the first four years of a fallow field, increasing more from the fourth to the eighth year, then decreasing as the vegetation continues to get older. Back in the U.S., Fiorella and Ripple's (1993) study of successionary stages of Oregon temperate coniferous forests, found that near-infrared reflectance of mature forests were significantly lower than that of old growth areas. Green (1988, 1998) has studied the response of near infrared reflectance in xeric and mesic deciduous forests in Missouri, but hasn't investigated how near-infrared changes in response to age class.

This discussion of factors producing particular leaf morphologies and findings related to stand age and near-infrared reflectance lead to two hypotheses that can be tested with a time series of multispectral satellite images:

> *Hypothesis 6-1: Natural, topographically controlled environmental conditions will produce differences in reflectance that can be explained by tree and leaf adaptations to mesic or xeric environments. Xeric forest*

vegetation residing on summits and areas with low water availability will tend to exhibit higher levels of near-infrared reflectance than stands residing in valleys.

Hypothesis 6-2: Forest areas recently harvested and in early stages of succession will tend to exhibit higher degrees of near-infrared reflectance a more xeric look than stands that have not been subject to such disturbance.

The goal of this chapter is to determine what human induced patterns are revealed in a time series of Landsat MSS images. I seek to answer the questions presented at the end of Chapter 5 by testing the hypotheses presented above To do this, I develop a spectral mixture model capturing the influence of mesic and xeric forest canopies. However, before this spectral mixture analysis can be undertaken, several *non trivial* image processing and GIS activities must first be completed.

Methods

Spectral mixture analysis requires the removal of other sources of variability that cannot be attributed to the land cover itself. Mertes, Smith and Adams state:

> A remotely sensed, multispectral image encodes information on atmosphere, lighting, and instrument conditions as well as information on the properties of surface materials. In addition to these potential inputs, every pixel may include information on a mixture of surface materials. In order to extract information regarding the surface materials, one must account for all of these effects (1993: 287).

In this chapter, several image processing steps (Figure 6-2) are undertaken in an attempt to remove sources of variability that cannot be attributed to land cover. These sources of variability, along with the step that addresses them, are listed in Table 6-1 (also refer back to Chapter 5, Figure 5-4).

*** Table 6-1 about here ***

*** Figure 6-2 about here ***

Once these nonhuman produced sources of variability are removed, several other procedures and GIS products are needed for SMA change analysis (Figure 6-2, Steps 6-9). This section describes the nine steps required to prepare the images for analysis

Step 1. Image Sampling

Image sampling removes several sources of unwanted variability in reflectance (Table 6-1). Several sampling decisions are required. Location of the study is the most fundamental decision and was described earlier in Chapter 3

The next step is to identify possible Landsat MSS images acquired of the area. Recall Chapter 5, Figure 5-3 which inventories Landsat MSS and TM images of high quality (0-10% cloud cover) for the five county study region. Satellite images are costly, consume valuable computer storage and take significant amounts of time to process, so one cannot simply process every image available in this Figure. The decision related to how many images are required for the study and what images to buy is crucial. The choice rests on three considerations: 1) how many images can one afford; 2) how many images are required to "critically sample" the phenomenon of interest; and 3) what season will provide the best opportunity to observe the phenomena of interest.

The first consideration is self explanatory. The second consideration, critical sampling, is described reasonably well by Siegal and Gillespie (1980). Any phenomenon we wish to monitor over time via satellite images could be conceptualized as having a cycle or function. For example, a forested area that is cut for timber may, the day after cutting, reveal significant observable traits (e.g., exposed soil) that are spectrally very different from the way it looked prior to vegetation removal. But as time progresses, successionary processes take over, which eventually, at some time in the future, the observable "cutting footprint" in the physical landscape may be completely overshadowed by secondary growth. At some point in the future evidence of the disturbance may disappear. It is the analysts job, then, to make sure that the image sample strategy adequately captures this cycle.

*** Figure 6-3 about here ***

Siegal and Gillespie utilize a sine wave to illustrate this point (Figure 6-3). Suppose one full sine wave cycle represents a timber "rotation" cycle often used in timber management. The beginning of the wave represents the moment when the forest stand is cut. The sine wave represents the successionary growth cycle and completes when the stand is at the same age as when it was prior to harvest. Figure 6-3 represents three different sampling scenarios: undersampling, oversampling and critical sampling. Undersampling cannot complete the reconstruction, oversampling wastes time, and money (in terms of images and human resources). With critical sampling, just enough images are sampled to adequately reconstruct the cycle.

There are many human activities described in Chapter 4 that we hope to critically sample. Many of these are reconstructed fairly easily. For example, direct actions that convert forest to some kind of development, such as a building, would result in a landscape disturbance that remains for 10, 50 or perhaps even more than one 100 years. Two images, one before and one after the point of construction, would adequately sample this phenomenon (assuming that the construction is large enough to be captured with MSS' spatial resolution)

Various methods of forest cutting and regrowth are the phenomena I am most concerned about undersampling. It is an important activity in forests in this region and has the likelihood of having the shortest observable temporal extent. The average rotation ages for the dominant forest types (see Chapter 3, Table 3-1) are around 100 and 90 years respectively (Spencer, *et al.*, 1990: 7). Therefore, the twenty-five-year lifetime of the Landsat program undersamples the cutting cycle. Aside from using additional sources of information (e.g., aerial photos or map resources) we are forced to live with this lifespan limitation. But, given that the rotation period is so long, it was decided that an image sampling frame of one image approximately every 10 years has a high likelihood of identifying a cut in this 25-year period if it occurs.

Once the decision on the number of images is determined, the issue turns to consideration of seasonal and weather effects related to image sampling. Clearly, vast differences occur as a result of the changes in seasons in temperate deciduous forests such as the ones found in Indiana. A satellite image taken in winter, when no leaves are on the trees, would be vastly different in information content than an image taken in the summer. Unless the analyst was interested in investigating what information is revealed in images taken over several seasons,[3] the analyst, wishing to control for the effects of season and weather on land cover, would be wise in selecting images from the same season, month, week or day of the year.

After these sampling considerations, three MSS images, all taken in the month of September, were selected for study (recall the circled points in Figure 5-3[4]). Their dates are 9/30/72, 9/1/85 and 9/28/92. All were acquired through the North American Landscape Characterization (NALC) program (USGS, 1997).

Step 2. Image Preprocessing

The images were checked for sensor produced artifacts, namely striping and speckle. Striping is caused by differences in the sensitivities of the MSS sensors (Campbell, 1996). The 9/28/92 green band revealed slight striping effects. These could not be removed since the NALC data were received already georeferenced.[5] The striping was minimal and it does not appear to have caused significant problems in later analysis. A second sensor related artifact, called speckle, was also detected in the green band of the 1985 scene. Speckle is a result of slight power surges in the scanner as it acquires an image. Unfortunately, there isn't a fix for this problem. This caused later some slight difficulties in interpreting other remote sensing products (e.g., endmember fractions) using the 1985 images. However, being aware that speckle exists helps interpretation immensely.

Since the NALC data arrived already georeferenced, I did not need to undertake this process. However, accurate georeferencing of images is of the upmost importance to studies of landcover change and it requires careful attention. Any misregistration between images could cause significant errors in results. Because of this, three different validation procedures were undertaken. First, NALC program officials utilize over 100 control points and ship the dataset when the georeferencing root mean squared error reaches a value of less than 1 pixel (NALC, 1997). Second, upon arrival, the MSS images were verified visually using a well georeferenced road GIS vector coverage supplied by colleagues at the Midwest Center of the National Institute for Global Environmental Change (NIGEC). Each of the three images was independently verified using this coverage and all matched the road network. Finally, third, similar bands from the time series of images (e.g., band 4 of each image) were compiled to produce a color composite. Any significant misregistration would produce a blurring in the resultant composite. The three NALC images passed all three of these tests while a fourth MSS image taken on 9/12/79 failed. The 1979 image was therefore dropped out of subsequent time series analyses.[6]

Steps 3, 4 and 5. Radiometric Calibration, Atmospheric Correction and Radiometric Rectification

Radiometric calibration is a process that converts satellite derived digital numbers (DNs) to at-satellite reflectance values (Robinove, 1982; Markham and Barker, 1986, Hill, 1991).[7] Atmospheric correction removes the variation caused by differences in atmosphere in each image and converts the at-satellite reflectance values to at-surface reflectance. Radiometric rectification normalizes the images to a base image and removes any additional noise[8] that was not removed in earlier steps. The procedure used here was developed by Hall *et al.* (1991) and the technical procedure I developed in described in Appendix C. Once atmospheric correction is completed, the digital numbers are converted to actual landcover reflectance: they represent the reflectance of the landcover with all other noise removed. Radiometric rectification makes sure the image spectra for the time points are directly comparable.

These steps are not always done in remote sensing analyses, nor are they always needed (Green, Schweik and Hanson, 1998). But the main advantages for undertaking these procedures is that (1) they remove additional sources of variance in reflectance that we would not want to associate with human activities, and (2) they produce at-surface reflectance values. This second point is important. By converting images to at-surface reflectance we now have physical measurements of landcover. We now can talk in terms of "forest X reflects 45 percent in the red visible band of MSS." This allows us to take measurements from one MSS image and compare that measurement with others from different times or different geographic locations. Comparisons over time and space can be made and spectral reflectance libraries can be generated that can be used by other studies. This cannot be done with the traditional classification analyses using satellite DNs (See Green, Schweik and Hanson, 1998, for a more complete discussion).

*** Figure 6-4 about here ***

Like georeferencing, these image processing procedures are vital to ensure that change analysis produces results that are reliable and valid. However, they involve procedures which do mathematical computations to the original satellite data and it is important to verify the results.[9] Figure 6-4 displays: (A) the original mean digital numbers; (B) the mean post-radiometric calibration and atmospheric correction at-earth reflectance; and (C) the mean post-radiometric rectification at-earth reflectance values for several consistently dark water bodies for the three time points. The high values in the original DN data in (A) in the green visible band (.5 μm) is a result of atmospheric distortion. Notice how this is significantly removed in (B). The spectra in (B) take on the shape of water bodies (refer back to Figure 5-2) but still exhibit slight differences that can be attributed to multiplicative atmospheric effects not removed. Radiometric rectification normalizes each of the time points to one base time point (9/28/92). The final results are shown in Figure 6-3 (C). Note how these spectra take on a similar shape as the example water spectra shown in Figure 5-2. A similar verification procedure was conducted for consistent bright locations in the area (e.g., quarry sites). Additional graphical documentation regarding this procedure is provided in Appendix H.

Step 6 Topographic Normalization

Shade produced by lighting geometry and topography adds another element of variation in the images that has not been removed by earlier procedures. Topographic shade is known to cause problems in classification analyses, causing shaded areas often to be classified as pine forests. Spectral mixture analysis studies usually model shade as one of the end members (see for example Adams, *et al.*, 1995). However, these studies have usually utilized TM images instead of MSS. The added bands supplied in TM images allow one degree of freedom to be given up by a shade end member. In the case of MSS, the attempt was made to remove shade since the four bands of MSS only allow three end members (# bands -1) to be modeled. If shade is included as an endmember, this would leave only two others analysis. It is preferable if the shade could be removed through topographic normalization (Jensen, 1996).

Only partial success was achieved in the topographic normalization process. An Idrissi™ model was developed to remove topographic shading based on a 7.5 meter digital elevation model of the area. A complete write-up of the procedure is included in Appendix E, and a graphic example of a pre-procedure and post-procedure 9/28/92 color composite image is shown in Figure 6-5. Notice how the topographic shading that exists in 6-5 (A) is significantly removed in Figure 6-5 (B). Figure 6-5 (C) shows the results of validation. Spectra for test locations not in shade remained the same after normalization while spectra for per-normalization shaded areas show an increase in reflectance after the procedure was completed. The shading that is left (Figure 6-5 B) is either dark reflectance caused by differences in valley versus summit vegetation reflectance, or, "smaller" topographic differences not captured accurately by the 7.5 minute digital elevation model. In short, this procedure removed some, but not all of the shade in the images. A shade endmember would be needed after all.

*** Figure 6-5 about here ***

The final images to be used for analysis are presented in Figures 6-6, 6-7 and 6-8. To improve readability, only a portion of the Morgan-Monroe forest, delineated by a black boundary, is shown.

*** Figures 6-6, 6-7 and 6-8 about here ***

<u>Step 7. GIS Development</u>

In order to study institutional incentives of various public forest areas both in this and subsequent chapters, several GIS vector layers were acquired and processed using an

Arc-Info™ GIS. Management units or "tract" layers for the state forests were provided by the Morgan-Monroe property manager. The director of the Midwest Center for the National Institute for Global Environmental Change provided other GIS layers such as the roads of the area and national forest boundaries (required for Chapter 7's analysis). Further, to assist in controlling for the effects of topography in subsequent analyses, a mosaic of the 7.5 minute digital elevation models (DEM) provided by the USGS was created.[10] A slope layer and an aspect layer were also created using this DEM mosaic. These were helpful in the earlier topographic normalization process and in other instances when I wished to control for the effects of topography-sun relationships.

Step 8. Spectral Mixture Analysis (SMA)

Chapter 5 provided a summary of SMA. This section will provide a brief, but important, review of the techniques applied to the time series of south-central Indiana MSS images, highlighting the important processes and decisions. For interested readers, a more complete graphical depiction of the SMA process and products for this particular forested location is provided in Appendix I.

To my knowledge, no "spectral library" of pure land cover elements in south-central Indiana exists. Further, no field spectrometer was available to collect field spectra of pure sites such as quarries. Consequently, extreme end member locations—landcover areas representing "pure" entities on the ground—were identified using the 9/28/92 image. I expected to identify several potential endmember candidates, based on three components: (1) the leaf morphology theory described earlier; (2) field knowledge of the south-central Indiana landscape; and (3) prior SMA literature. Endmembers used in past studies include extreme spectra representing: water, soil, green (live) vegetation, litter, and shade (Sabol, Adams, and Smith, 1992; Ustin, Smith and Adams, 1993; Adams, *et al.*, 1995; Shimabukuro and Smith, 1995). For this study, I decided to identify locations for soil, xeric vegetation, mesic vegetation and shade.

The ENVI™ software package was useful for this component of the study. By using its "pixel purity index" functionality, the analyst can identify a subset of candidate pixels in the image that are extreme in their spectra. Once these candidates are identified, 3-D scatterplots of their values at Band 1 (green visible, .55 μm), Band 2 (red visible, .65μm) and Band 4 (near infrared, .95μm) can be plotted. ENVI functionality includes the ability to rotate the 3-D scatter plot so the "data cloud" can be better understood and extreme pixels can be highlighted, reviewed and selected as endmember candidates.

Since limitations in the number of MSS bands force the analyst to choose only three endmembers, this 3-D scatter plot was first used to remove water areas that were not of interest for this research question. Water bodies could easily be identified, for they are extremely dark bands 1, 2 and 4. Water body pixels were "clipped" and removed from the images (Figure 6-9). Clouds and cloud shadows in the 1972 image were visually identified, delineated and clipped out of all three images.

Identification of the other endmember candidates—spectrally "pure" areas representing soil, xeric vegetation and mesic vegetation—involved a series of interactive steps from the computer, to the field for reconnaissance, and back to the computer. For example, in a similar fashion to the water example, extreme soil locations were identified using the 3-D scatter plot and these pixels were then highlighted on an R-4, G-2, B-1 color composite of the 9/28/92 image. Particular pixels of interest were inventoried in the field.

By applying differential global positioning systems and converting this location to a point layer I could verify to within 5 meters accuracy that the pixel of interest was, in fact, visited. Figures 6-10 and 6-11 provide an example of this process for soil endmember identification. Similar reconnaissance was conducted to verify candidate xeric and mesic vegetation locations.

*** Figures 6-10 , 6-11 and 6-12 about here ***

The spectra for candidate endmember locations are provided in Figure 6-12. Three soil candidates, four xeric (bright) vegetation candidates and three mesic (dark) vegetation candidates were identified. Several SMA models were run combining various soil, xeric and mesic/shade candidates. The output for each MSS time point is four images, three representing the percent of each endmember (soil, xeric vegetation and mesic vegetation) for each pixel and the fourth representing the RMS error or goodness of fit of the model. Since shade was still in the image, to some degree, the mesic vegetation endmember actually picks up some of the influence of both of these factors. Other components of shade are not modeled well and contribute to the RMS image values.[11] Areas that are not well explained by the model are easily identified in high values in the RMS error image. These areas can be reviewed and possibly selected as another endmember candidate.[12]

When SMA is being applied to a single image, two criteria are used to select an appropriate final model: (1) that spectral variability is largely accounted for; and (2) that it produces endmember percentages between 0 and unity (Ustin, *et al.*, 1993: 345; ENVI, 1998). Time series work adds a third criteria: that the model satisfies the first two criteria for *all three* time points. Given the limitations in MSS degrees of freedom and that shade still exists in the image, finding the model that satisfied all three of these criteria is a difficult task and wasn't fully accomplished. The spectra for the chosen endmembers are shown in Figure 6-13 and their values are provided in Table 6-2. The model chosen uses a soil location that is a cleared agriculture field, a xeric vegetation location that resides partially on a summit and partially on the upper banks of a south-west facing slope, and a mesic vegetation location that resides in a valley area that is somewhat shaded. This third endmember thus captures the influence of both dark mesic vegetation and shade. This initiates a "reflectance spectral library" of "pure" landcover features for south-central Indiana.

*** Figure 6-13 about here ***

*** Table 6-2 about here ***

The fraction and RMS error images for each time point are provided in Figures 6-14 through 6-16. For ease of reader interpretation, only the northern portion of the Morgan-Monroe forest is shown. In each of the three figures, three fraction images are presented from left to right: (1) % soil, (2) % xeric vegetation, and (3) % mature vegetation and shade. The model's root mean square error for each pixel is presented in the lower right image.

One method of assessing the model's fit is through visual inspection. Note, for example, the circled area in each of the three Figures 6-14, 6-15 and 6-16. Encompassed in this circle are buildings used by the forest property manager. Notice how in each of the time points within this circle the soil fraction image is bright. The buildings have been in this location since before 1972 and therefore the reflectance spectra exhibits a high similarity to the soil endmember throughout time. This high degree of soil results in low (dark) values in the other two vegetation endmembers. The RMS error at this location is quite dark, meaning that the model fits this location well.

*** Figures 6-14, 6-15, and 6-16 about here ***

The model presented here provides the best fit of all the possible endmember combinations in regard to the three criteria specified above. But even the best model doesn't satisfy the criteria entirely. While the fractions for each endmember in each time point tend to stay in the vicinity of the zero to one range, some do fall below zero or spike above one. Evaluation of the RMS error images for each time point revealed that in many cases the areas not particularly well modeled fall along boundaries of the forest property and are land cover types of little interest in this study. Most of these high error areas are land cover such as active agriculture or wetlands adjacent to water bodies clipped and removed from the image. One such example of this is shown in Figure 6-17. The bright areas are pixels with high RMS error.

*** Figure 6-17 about here ***

Given the four-band limitation in Landsat MSS scenes, we cannot expect that a three endmember model will explain fully all spectral variation found in an image. While attempts were made to mask out land cover (e.g., water and cloud shadow) that were of no interest to this study, clearly there are areas that are not modeled well. What is important here is that the final SMA model is the one that does the best job in satisfying the three criteria for selection and appears to model the region of interest–the forested areas–reasonably well *for all time points*.

Results

Until now, this chapter has focused on the methods to produce endmember fraction images for the three time points. These images can now be used individually or together to begin to analyze land cover composition at single time points and land cover change across the 1972-1992 period.

The rest of this chapter is devoted to a spatio-temporal land cover analysis of a portion of the Morgan-Monroe forest. Given the careful attention to verification of procedures throughout the image restoration and topographic normalization process, the patterns that remain in the images can be attributed to either: (1) "naturally" produced change (e.g., weather, hydrology) and (2) human produced change. The next step is to analyze change that appear to be a consequence of "natural" forces. Once these natural patterns are understood, or at least identified, the analysis then turns to our ultimate goal–a focus on anthopogenically produced spatial and temporal patterns in MSS images.

Change Produced by Natural Phenomenon

The Mesic-Xeric Vegetation Distinction and Weather Induced Variability

Figure 6-18 displays in grey shading the infrared Band 4 of the 9/30/72 MSS image with a portion of the Morgan-Monroe reference forest delineated. The image has been fully processed through topographic normalization. Lakes and ponds, along with bright clouds and cloud shadows have been removed from the analysis.[13] Recall that band 4 captures the infrared reflectance at the wavelength of 95 micrometers and therefore vegetation appears quite bright. There is a major north-south road on the western side of the image with little vegetation (it is dark). A close examination of the vegetation areas reveals a distinction in brightness and darkness that fall generally in high and low elevation areas. It is important to note that the topographic normalization step removed much of the shadowing that can be attributed to topography and lighting geometry, yet in this image there still are significant visual differences in vegetation reflectance. In general, mesic areas (e.g., valley bottoms) appear to have lower values in infrared reflectance, than do drier areas (e.g., summits). See the examples (A) and (B) in Figure 6-18. Therefore, valley areas appear darker than summit areas. This phenomenon becomes even more apparent in the 1972 xeric vegetation endmember fraction (Figure 6-18 A).

*** Figure 6-18 about here ***

However, visual interpretation isn't enough proof. A difference in means test would be helpful to verify that this apparent brightness/darkness difference is indeed one of high elevation versus low elevation (Figure 6-19 A). Random high and low elevation areas were delineated for a sub-area of the forest using the digital elevation model (Figure 6-19 B). These areas were then overlaid on the 9/30/72 xeric endmember fraction image (Figure 6-19 C). The difference in means test leads to the conclusion that the average percent of the xeric endmember in high areas exceeds that of low elevation areas by approximately 5 percent (Figure 6-19 D). The expectation is confirmed: In the 1972 image, summit areas are indeed more xeric than valley areas.

*** Figure 6-19 about here ***

The argument could be made that this finding may actually be a consequence of residual shadowing: that the shadows resulting from lighting geometry and topography were not adequately removed by the topographic normalization procedure. Figure 6-20 helps to reject this hypothesis. It presents a side-by-side comparison of Band 4 images for the three time points of this study. In the 9/30/72 image, the distinction between valleys (dark) and summits (bright) can be clearly identified. This is also true for the most recent 9/28/92 image. However, in the middle year, 9/01/85, this distinction is much less apparent. Notice how the dark-bright distinction nearly vanishes in the circled area in the 1985 image while it is readily apparent in the other two images. Consequently, this brightness/darkness distinction that we see in the 1972 and 1992 image cannot be attributed to lighting geometry and topographic shadowing, for all three images were taken at almost the same exact time of the day,[14] and the effects of topographic shadowing were removed from each image using exactly the same procedure. If topographic shadowing were the culprit, we would see the same shadow effect in the 1985 image. Figure 6-20 provides clear evidence that topographic shadowing is not the reason. Figure 6-21 displays comparable side-by-side xeric endmember maps where this 1972-drier, 1985-wetter, 1992-drier phenomenon is also apparent.

*** Figure 6-20 about here ***

*** Figure 6-21 about here ***

Why then does the brightness/darkness distinction practically vanish in the 1985 image? A review of precipitation data for these three years provides a powerful explanation. Each of these years have similar temperature histories, but the annual rainfall measurements for 1985 are higher than these other two years (Figure 6-22). Moreover, 1985 is the only year of the three that was proceeded by an above average wet year. This finding lends support to the prior research by Green (1998) on leaf morphology described earlier. From this data, it appears that throughout the region, the tree's best growing strategy for the year is controlled by the precipitation patterns that occurred the year before. The high precipitation in 1985 and its previous year yields more available water even in summit regions, thus producing an image with a more mesomorphic-like reflectance for that year. Whereas in 1972 and 1992, the earlier year was drier, hence producing a more regional xeromorphic-like reflectance. This provides a very good explanation as to why the brightness-darkness phenomenon is significantly reduced *throughout* the 1985 image yet is so prevalent in the 1972 and 1992 images.[15]

*** Figure 6-22 about here ***

This finding, while interesting in and of itself, presents a challenge for the rest of the study in terms of how to identify land cover change attributable to humans. By controlling for season in image selection, it was hoped that seasonal variation would be diminished or nonexistent. However, the degree to which this forest appears to have responded to the higher precipitation year of 1985—nearly vanishing the xeric-mesic distinctions–was an unexpected result. This adds additional variation in the time series analysis that cannot be attributed to human action. The rest of the change analysis will have to be undertaken carefully, keeping in mind that this weather induced variation exists in the image data.

Other Apparent Naturally Produced Phenomenon

Additional reviews of color composite images and change maps of this forest resulted in the discovery of another naturally occurring phenomenon related to topography. In order to determine what it was, the finest scale geological map of the area was acquired.[16] This feature is best shown on an available Landsat TM image from September 1997 for the area. Figure 6-23 presents a color composite of this image, where TM Band 4 (near infrared at .76-.90 μm) is mapped to the color red, TM Band 5 (mid infrared at 1.55-1.75 μm) mapped to green, and TM Band 7 (mid infrared at 2.08-2.35) mapped to blue. In the image there appears to be a northwest to southeast running "ribbon" of hills that look more clustered and condensed in some areas. A review of the geological map revealed that a major fault—the Mount Carmel Fault–which begins in this forested area and runs south. This fault region (Figure 6-23) appears to have altered the shape of the hills in its swath, most likely altering water flow and therefore producing slight patterns in forest vegetation growth. Any comparisons later searching for human induced patterns in vegetation, needs to be aware of this phenomenon.

*** Figure 6-23 about here ***

Going by the geologic map, this fault also appears to separate two distinct bedrock areas. The northeast side of this fault consists primarily of siltstone, shale, sandstone and thin limestone. The surface geology of the area is documented as thin stoney soil (Harke and Gray, 1989). The southwest side of this fault line is more complex and with more prevalent coarse-grained limestone bedrock. Comparing the bedrock patterns in these maps with the image spectra produced no significant or particularly important geologic produced patterns in vegetation exist that won't be controlled for if we remain cognizant of hillslope issues.

To summarize, there appears to be three important naturally occurring phenomena we must be cognizant of as we begin to investigate anthropogenically produced patterns in the landscape. First, there are obvious differences in vegetation reflectance in valleys and summits. Second, change analysis must be cognizant and careful about conclusions made about change given that the 1985 image was taken during a particularly wet season. We must be careful not to attribute this change to human activities when in fact they may be weather produced phenomenon. Finally third, the analysis must be careful not to make false conclusions about vegetation patterns that might be due to the unusual topographic effects caused by the major fault line in the area.

Change Produced by Human Activities

Now that we have developed a sufficient understanding of naturally induced change in the images, we are now -finally—ready to investigate the MSS time series for sensitivity to forest change that is a result of human effort. Previously, Chapter 4 summarized the various forest management direct activities that are undertaken by forest property managers, their staff, contractors and forest users. In general, these activities were organized into preservation related activities, commodity related activities, and recreation related activities. The activities that will be reviewed here are listed in Table 6-3. Representative locations of known activity will be identified, geographically referenced and tested for MSS spectral mixture sensitivity

*** Table 6-3 about here ***

What follows is a change analysis of linear unmixing results for each human activity listed in Table 6-3. Given time and space constraints, and because of the hypothesized mesic-to-xeric distinctions presented early in this chapter, primary analytic emphasis will be given to explore changes in the xeric endmember fraction images. In some instances, soil trajectories will also be explored. Rarely will the mesic/shade fractions be used, for the shade component is less interesting theoretically, and that endmember, capturing the influence of both mesic vegetation and shade, doesn't appear to model as well as the other two endmembers. For each type of activity presented in Table

6-3, a hypothesis will be made related to the temporal trajectory (e.g., values on the 1972, 1985 and 1992 images) of the percent of xeric endmember fraction. The hypothesis will be tested using known locations of human activity at the Morgan-Monroe forest that was acquired from the detailed records (including in many cases good maps) stored at the property manager's office.

Each analysis section on human activities will focus in part on patterns found in the xeric fraction images for the three time series points. One method of analyzing temporal fraction images together is to create a multitemporal color composite based on the same endmember from each time point. Figure 6-24 displays such a "change map" for the xeric fraction image for the three time points. The study portion of the Morgan-Monroe forest is shown. Overlaid on this map in black lines is the vector coverage of management unit or tract[17] boundaries used by the property managers in their day to day activities.[18]

*** Figures 6-24 and 6-25 about here ***

In Figure 6-24, major changes are represented by saturated (rich) colors and minor changes are represented by a less saturated, more pastel looking color. The continuous nature of the xeric fraction percentages produces subtle changes in color that make interpretation more difficult than if one used a classification map, but it is more true in representation of the change that is occurring on the ground.[19] At the extremes, pixels in rich colored red represent percent xeric vegetation that were very low in 1972 and 1985, and were very high in the 1992 image. Pixels rich in blue color represent a change from a high percentage of xeric vegetation in 1972, to lower percentages in 1985 and 1992.

Pixels rich in green depict locations that had low xeric vegetation in 1972, high xeric vegetation in 1985, and low xeric vegetation again in 1992. A full description of the meaning of the colors is provided in Figure 6-25 Note that much of the image is represented by shades of pastel colors This means that the changes in percent xeric reflectance are more subtle: to a large extent the changes that occur are not extreme but rather are smaller shifts between more and less xeric vegetation.

For each type of human activity analyzed, it is especially important to be cognizant of the spatial and temporal scales related to the forest disturbance, for this has critical importance as to whether their impact will be detected in this three-time point set of satellite images. This returns back to the earlier discussion regarding temporal sampling of images and whether the phenomenon (in this case human disturbances) will be critically sampled (Siegal and Gillespie, 1980). The date of the disturbance in relation to when the images were acquired is likely to be an important factor as to whether the disturbance is detected. A small spatial scale forest disturbance that occurred many years (e.g., 10) prior to when an image was taken will have less of a chance of being detected because of vegetation regrowth. Special attention should be made to understand when a cut occurred and how many years have past before the next image was taken.

Mature Forest Protection (Preservation Activity)

The first activity to be investigated is one where humans decide to leave an area alone. In many publically managed forests, some tracts have the designation "old growth." As discussed in Chapter 5, very few areas in Indiana actually contain virgin timber, so most of these tracts are instead "mature" secondary succession stands or stands not easily accessible for other purposes. In the Morgan-Monroe reference forest, two such designated old growth tracts were selected for study. The areas they encompass include the two triangularly bounded areas enlarged in Figure 6-24 (A). Within these tracts, two mesic and two xeric stands were delineated using DEM information. The two xeric stand areas, about 11 acres together in size, reside on higher elevation summit areas and represent protected xeric forest vegetation environments. Similarly, two delineated stands in lower elevation areas, one for each tract, were selected to represent protected mesic forest vegetation environments. These four stand areas are highlighted in Figure 6-24 (A).

*** Figure 6-26 about here ***

Figure 6-26 presents the mean xeric vegetation percentage "temporal trajectories" for each of these four stands. If we assume (1) that trees continue to grow a larger root system over time, thereby continuing to improve access to sources of water, and (2) as tree canopies get larger a higher proportion of leaves are protected from direct sunlight, we would expect the xeric fraction in these stands to decrease over time. The mean trajectories for each of these regions, representing eighty-nine eighty square meter pixels as a group, follow this pattern in general, with an added "dip" in the 1985 year. This drop is best explained by the high rainfall during the 1984-85 period producing even lower than normal xeric endmember fractions for that year. The vegetation in 1992, exhibits what we would expect: it appears less xeric than 20 years earlier in 1972. Note also from Figure 6-26 that two mean trajectories for vegetation in xeric environments have, for the most part, higher xeric endmember fractions throughout time than vegetation in mesic regions. This confirms the expected relationship.

There is no history of human or natural disturbances (e.g., windthrows) in these two tracts. These "xeric fraction trajectories" can therefore be used as reference trajectories against which other analyses can be compared. Essentially, they reveal what a forest canopy in this region should look like in terms of the xeric endmember when no human or natural disturbances have occurred.

Road Construction and Maintenance (Commodity Related Activity)

Disturbances humans create as a result of their commodity related activities can be witnessed at both broad and fine spatial and temporal scales. Broad land cover patterns as a result of commodity-related activities are apparent in this time series of images. Developed areas (e.g., buildings, roads) emit bright reflectance in the visible bands of the MSS images and are high in the soil endmember fraction images. Distinctly bright in bands 1 and 2 at all time points is the major four-lane highway that runs north-south (Figures 6-6 through 6-8). Smaller developed areas within the forest property can also be found. The forest property manager complex, built prior to 1972, can be identified in both the individual visible band images (Figures 6-6 through 6-8) as well as in the soil endmember fraction images (Figures 6-14 through 6-16). These are relatively large developed areas that are well maintained.

But even these well-maintained areas exhibit changes. The major section of highway that cuts through the forested area is enlarged in the change map of Figure 6-24 (B). The road is depicted by very dark black pixels. Notice the yellowish and greenish pixels that surround the edges of this road. Green represents pixels that have a low percentage of xeric vegetation in 1972, have a higher percentage in 1985, and then have a lower percentage again in 1992. The yellow pixels are areas that were low in 1972, and then high in xeric vegetation in 1985 and 1992. This can also be identified through a close examination of the individual visible band images (Figures 6-6 through 6-8). These changes are best explained when one reflects on the effort that state and federal transportation agencies must exert to minimize vegetation encroachment along roads and highways. In 1972, the highway was younger, and exhibits a higher percentage of the soil endmember for this region. Soil was probably exposed from the highway's construction or widening. As time progresses, secondary succession vegetation continues to encroach on the edges thus producing an increase in the xeric endmember fraction of some images in the 1985 image. Places that remain better maintained by transportation departments continue to display a high percentage of xeric vegetation while places that aren't begin to lose xeric vegetation and gain in mesic vegetation as roadside plants mature.

No new public road construction occurred in this public forest over the 1972-1992 period (Stein, 1998). The existing networks of smaller roads within the Morgan-Monroe property are harder to identify visually using MSS data in forested conditions. As Wilkie and Finn (1996) suggest, there is the possibility that a MSS image could detect a road's existence even though it may be smaller than the theoretical spatial resolution of the sensor.[20] If there was no canopy cover above the road itself throughout time, we would expect the roads to be represented by curve-linear sets of grey or dark pixels in the xeric fraction change image in Figure 6-24. Similarly, we would expect curve-linear sets of white (bright) pixels in a soil fraction change image (Figure 6-27). A GIS layer representing these two lane roads was overlaid on this and several other color composite change images to determine whether the roads are detectable and recognizable to human interpretation. Not surprisingly, the answer is "sometimes." It depends on whether or not the road is sufficiently broad through time to continuously pick up soil reflectance, and it depends on what color composite is used. One road network is detectable in the soil endmember change map (Figure 6-27) that isn't readily apparent in the xeric endmember map (Figure 6-24). Interestingly, side-by-side color composites of end members for each time point (e.g., Red-1972 xeric, Green-1972 soil, Blue-1972 mesic) (not shown) reveal slightly higher soil fraction values in 1972 than in later years. This could be because the road networks were younger and that the adjacent trees had not grown tall enough to cover the road fully.

*** Figure 6-27 about here ***

Logging roads are also built within these forests. Several tracts had topographic maps drawn with plans for logging roads. Effort was made to locate these on the MSS and fraction images with no success. It appears that the spatial width of logging roads along with existing overstory canopy minimizes the likelihood that we can identify these types of human disturbances using MSS images. They very well may be detected using the better resolution TM imagery.

In summary, road construction and maintenance is probably the most obvious broad spatial scale human activity in public forests in this region. Tree cutting could be even more significant, but because of its scattering across the landscape may be more difficult to identify without a more fine spatial scale examination. This will be conducted in the next section. The lesson from this analysis is obvious: the likelihood of detecting human road development and maintenance using MSS imagery will be higher if the image was acquired near the time of road construction and depends on the size of the road being constructed. Four lane highways are very identifiable, two lane roads more difficult to detect, and logging roads and trails nearly impossible to recognize. Where roads are identified, adjacent vegetation often exhibits xeric qualities that capture roadside vegetation maintenance. Maintained shoulder areas continue to look xeric over time while non maintained areas gradually become more mesic in character.

Forest Conversion for Development (Commodity Related Activity)

Another important commodity related activity often undertaken is new building construction and other related development. Within the Morgan-Monroe reference forest area, only one new construction site was identified that occurred within the study period. In 1980, the forest manager's office building burned down, taking many of the prior to 1980 forest management records with it. In 1981, the building was rebuilt, and with it several pole barns were added expanding the developed area (Stein, 1998). This construction area, about 3.3 acres, is highlighted in Figure 6-27 (C).

We'd expect that the soil member would be first lower in 1972 because of the existing vegetation, then higher in 1985 where vegetation was replaced by buildings and parking lots and then remain high in 1992 as the new buildings remain. The actual trajectory for the soil endmember is shown in Figure 6-28 and supports this hypothesis. No hypothesis could be made about the xeric or mesic/shade fractions, but their trajectories too make good sense. Prior to 1980, the proportions of xeric vegetation, soil (building/parking lots, etc.) and mesic vegetation/shade is roughly equal. Then, after the new development in 1981, the soil endmember fraction rises to over 40 percent of the three acre area in the 1985 image while both vegetation fractions drop. The mesic vegetation/shade drops most significantly, giving the appearance that older vegetation may have been removed to make room for the pole barns.[21]

*** Figure 6-28 about here ***

In summary, conversion from forest to some relatively permanent developed area is readily apparent in MSS imagery even when the activity occurs in relatively small geographic area. The dramatic spectral distinction between soil and other non vegetated matter and forest vegetation makes identification relatively easy.

Silviculture Activities (Commodity Related Activity)

Several different silviculture activities are undertaken by property managers in this forest. Timber harvest techniques include: group selection cuts, commercial thinnings and sometimes single tree selection cuts. Group selection cuts remove all of the trees in a relatively small, contiguous area (Kimmins, 1992: 60). This type of activity, like a small clearcut, usually leaves a gap in the canopy. The other types of cutting, improvement, thinnings or selection cuts, remove individual marked trees from a scattered geographic area (e.g., a tract) (Ibid.). These types of cuts leave less dramatic "footprints," which are much harder to detect, visually, in the MSS images.

A number of these cuts have occurred in this reference forest over the 1972-1992 period. Identification and delineation of these cuts involved the triangulation of several information sources. First, two recent Landsat TM scenes, one taken in September 1997 and the other taken on the same date as the latest MSS scene, 9/12/92, were reviewed. The improved spatial (30 meters squared) and spectral resolution (especially the added mid-infrared band) provided a much improved visual picture of cut footprints on the ground. Using the ERDAS Imagine™ and ENVI™ raster GIS software, TM color composites (usually the R-5, G-6, B-7 infrared, midinfrared composite) and MSS change map images were displayed side-by-side, each having the tract and road GIS layers overlaid upon it. This provided an excellent working environment to identify cut areas (especially cuts that occurred in the 1980s and early 1990s) and to identify the tracts that they fell within. The MSS fraction change maps helped to identify areas that were cut in the earlier time points (e.g., 1970s). Areas were identified and delineated using "area of interest" functionality in the Imagine™ and ENVI™ software packages (similar to the way forest stands were delineated in Figure 6-24A). Access to the property manager's tract management records provided excellent information (including maps drawn on topographic maps by the managing forester) on where cutting occurred. The TM images, the forest records, and the MSS change maps made delineation of cutting areas fairly easy, especially when the cut was a group selection leaving an opening.

Figure 6-29 displays a time line of various tracts subject to cutting activities of different spatial extent and different cut types (e.g., group selection, thinning, etc.).[22] In parentheses next to each name, is the approximate area (in acres) for that sampled area of interest. One pixel represents a little less than two acres in size. It is important to note that each cut area represents several, often many, MSS pixels at roughly 80 square meters for each pixel. Given that vegetation grows back, it is especially important for MSS sensitivity analysis to understand when exactly the disturbance occurred.

*** Figure 6-29 about here ***

Cuts Between 1985 and 1992: In general, since the residual of a cut is a younger aged stand, I hypothesize that cutting will produce an area that exhibits a higher level of xeric vegetation. For cuts that have occurred between 1985 and 1992, we would then expect the trajectory for the xeric end member fraction to be lower in 1972, remain a similar level or lower in 1985 as this vegetation continues to get older, and then as the result of the disturbance, increase in 1992. Figures 6-30 and 6-31 show the cuts that did, and did not follow this hypothesized trajectory. Included for comparison on both of these graphs is the mean trajectory for the protected "reference" stands with standard deviation bars. Of the six cut locations surveyed that did occur during the 1985-1992 period, representing approximately 30 acres or about 19 pixels, all but one followed the expected trajectory (Figure 6-30). They all appear to take some drop in xeric percentages from 1972 to 1985 as a result of the increased precipitation in 1984-85. In 1992, they all have a higher percentage of xeric vegetation than the mean of the untouched protected reference stands. Two cuts (860, and 87P1) that were group selection openings are higher than one standard deviation above the mean of these reference forest areas. The others, group selection or thinnings are nearly above this point as well. While some of these stands remain within a one standard deviation of the mean of the protected forest, the 1992 year data demonstrates rather effectively that the MSS images are sensitive to openings and thinning activities.

*** Figures 6-30 and 6-31 about here ***

The one cut that does not reflect the expected trajectory is shown in Figure 6-31, a thinning cut with a relatively small removal (958 bdft/acre). This particular cut was difficult to identify on the change maps and on the images. It is quite likely then that the region cut away wasn't delineated correctly. Even so, this area takes on a strange trajectory, one that doesn't reflect the untouched stand trajectory either: it still should have a low point in 1985 due to the heavy rainfall. Nothing in the tract records or in the TM images help to explain why this particular area is different (e.g., different vegetation such as pine) from the others studied so far. Additional field reconnaissance is required to understand why this region exhibits such an unusual temporal xeric pattern.

Cuts Between 1972 and 1985: A similar analysis is provided for cuts that have occurred between 1972 and 1985. It is expected in this case that the tract would exhibit low xeric vegetation in 1972 for the tract will comprise relatively mature trees. If cutting occurs somewhere before 1985, it is expected that the tract will exhibit a higher percentage of xeric (young) vegetation in the 1985 image. Then, as this vegetation becomes older, it will become more mesic thus producing a lower xeric fraction in 1992. Of the eleven areas that were cut between 1972 and 1985 (Figure 6-29), seven support this hypothesis (Figure 6-32) and four do not (Figure 6-33). Interestingly, most of the eleven cases begin with xeric fractions in 1972 much lower than the mean of the protected forest areas. A review of the records of the protected forest tracts reveals they received these designations in 1992. They may then have been harvested sometime earlier than 1972. The eleven stands harvested between 1972 and 1985 probably were more mature vegetation than what existed in the preserved forest tracts at that time. This would explain why most of these tracts have lower xeric fractions in 1972.

*** Figures 6-32 and 6-33 about here ***

The cuts that follow the expected trajectory, shown in Figure 6-32, reveal a rather remarkable increase in the percentage of xeric vegetation in 1985. Moreover, given that these cuts probably are lower in the xeric fraction in 1985 because of the rainy year, this spike is quite striking.

The other four cuts shown in Figure 6-33, do not support the hypothesized trajectory The question is why not? Good explanations are available for all four cases. Two of the three thinning cases (78E and 82I) had insufficient cutting information in the tract file (e.g., maps). This resulted in problems delineating where these cuts occurred. They were not visible in the more recent TM scenes available and they did not clearly appear in the fraction change maps. This means that the wrong location could have instead been represented. Cut 82 I has a similar look to the untouched reference forest. Cut 78E has a strange trajectory that needs to be further investigated in the field. In the third case, a group selection cut (84L), the cut footprint was still visible in the TM image but fell in the strange topography of the fault area and was largely shadowed by the remaining trees on the slope above it. In this particular case, the mesic/shade endmember reveals an increase. In the fourth case (84M), a thinning cut, the documentation for the harvest contains a statement, made by the managing public forester, stating that special care was made to select trees individually so that the tract would continue to look like a mature stand. It is interesting to see how much that particular trajectory does in fact line up with the mean trajectory of the mature protected stands. It appears then, in each of the four cuts that do not support the hypothesis, there is another factor involved that can explain why they don't look as expected.

Cuts Before 1972: The final cutting analysis is one that investigates the trajectory of a cut occurring before 1972. In part due to the fire that destroyed property records, only one tract could be found that had been harvested prior to 1972. In such a case, we would expect that the 1972 image would exhibit the highest percentage of xeric vegetation, because the vegetation would be the youngest. Then, as time progressed, the vegetation would get more mature leading to a reduction of the xeric fraction in 1985 and 1992 and an increase in the mesic end member fraction. In the one case that could be identified (70A), this trajectory is supported (Figure 6-34). What was rather striking in this instance was the clarity in which the xeric change map revealed this history. It displays a pastel blue-looking color (recall Figure 6-25) in exactly the area that is delineated on the maps associated with that harvest in the property record files.

*** Figure 6-34 about here ***

TSI and Planting: Two other silviculture activities are undertaken by forest property managers in the area: "timber stand improvement" (TSI) and planting activities. TSI activities include coppicing[23] commercially desired species, thinning seedlings and saplings of undesired species and removal of grape vines (Indiana Division of Forestry, 1998). These activities are documented for tracts in the area, but occur in either very general areas or in very small geographic areas. While in the long term they may make a great deal of difference in the type of stand that exists in the tract, these individual activities are too small to be picked up by MSS images.

A similar story can be told related to planting activities with a strong exception in regard to pine plantations. Tract records reveal several planting activities have occurred in the region. For example, one major planting initiative occurred in 1984 where approximately 500 oak trees were planted in an area of about 2 acres (Indiana DNR, 1998).[24] This area, in total encompasses a little over one MSS pixel. Existing maps of the plantation were not drawn on topographic maps making it difficult to locate the specific pixel in which the planting occurred. Several other planting initiatives were identified in the tract records but involve even smaller geographic areas.

Pine plantations, on the other hand, are readily identifiable in MSS images. They have a rather unique appearance in the multispectral images exhibiting a darker reflectance in the near-infrared bands. Notice how the pine spectra in Figure 6-12 is the darkest vegetation across all bands in the list of endmember candidates. Because pine is so dark, computer generated classifications of multispectral images often categorize shadowed areas in the same class as pine. MSS images appear to be quite sensitive to pine plantations, but in the time period studied no new pine cutting or planting activities were identified.

To summarize, silviculture activities are one of the dominant activities in this forest. Several methods of cutting are used. The general hypothesis tested here is that a cut area will exhibit a higher percentage of xeric vegetation after the cut than existed prior to the cut. As time progresses after the cut, the young successionary vegetation will develop deeper root systems enabling them to access more water in broader soil areas. Gradually, the vegetation will begin to display more mesic qualities as they grow older. While there are several sources of variability still not accounted for in this analysis (e.g., stand species composition), overall the trajectories discovered in many cuts representing several hundred MSS pixels, provide strong evidence to support this general hypothesis.

Campgrounds, Trails, and Hunting (Recreation Related Activities)

The state and national forests in Indiana are popular places for humans to recreate. The Morgan-Monroe area is no exception. There is a major camping area, several hiking trails are in existence and hunting is permitted in many tracts.

The main campground on the property was built in the 1960s or earlier (Stein, 1998). Given this lengthy existence, we would expect the area to remain relatively stable in terms of the soil trajectory. Since no live tree cutting is allowed in this area, we would expect the xeric vegetation end member to take on a similar look to that of the protected forest stands. Figure 6-35 shows the actual mean trajectories identified for the 20 pixels comprising the campground. Surprisingly, the vegetation spectra do not reveal the same drop in xeric vegetation in 1985 as do most other study areas. There is a constant decrease in the percentage of xeric vegetation, which can be explained, in part, by the growth of the existing trees in the tract. Why this area is not as responsive to the rainy 1985 season is unknown. One possible explanation could be that particular management efforts have been made in the campground to encourage water runoff so camping areas are not sitting in pools of water. The percent mesic end member takes a strange drop in 1985 as well. The explanation for this is unclear.[25] But in 1992, it increases above the 1972 starting point as expected. Existing vegetation, as it gets older, appears to be moving from a xeric morphology to a more mesomorphic morphology. The soil endmember fraction also appears to be increasing over time. This could be a result of an increasing demand and "wear and tear" on the campground area as well reflect the common camping practice of harvesting small seedlings and saplings for firewood.

*** Figure 6-35 about here ***

Hiking trails in the region were also investigated. The property manager supplied a trail GIS layer for analysis. Several trails were constructed sometime between 1988 and 1994 Stein, 1998). Delineation of these trails and analysis of fraction trajectories revealed no major differences from that of the typical xeric vegetation spectra shown by the protected forest areas. It appears, not surprisingly, that the spatial and spectral resolution of MSS images do not sufficiently pick up reflectance that is a result of this type of activity. It is an activity that usually occurs beneath a thick forest canopy.

The same is true for tracts delineated as hunting areas. Animal grazing (e.g., deer) occur under forest canopy and disturb ground cover vegetation. It was not expected, nor was it discovered that hunting tracts reveal any significant reflectance differences compared to tracts designated as non-hunting areas

In sum, most recreational activities do not appear to influence the spectral response of MSS images. Camping areas are the one exception, and based on this one case, it didn't support the hypothesized fraction trajectories. The trajectory it did take is likely a result of a combination of no harvesting rules, special care for water drainage, and small openings in the canopy for tent and recreational vehicle parking. Depending on the size of a newly constructed campground, that is, if it is larger than 2-3 acres (about 2 MSS pixels) and if good maps exist of the location, it probably can be detected in MSS change maps.

Summary and Conclusions

The conclusion in Chapter 5 presented a set of methodological questions this chapter was to address. These questions are:

> *M4 Part 1) How well does the resolution provided by temporal sets of MSS imagery capture the grain of various forest management activities in South-Central Indiana using SMA as an analysis tool?*
>
> *M4 Part 2) What are the spectral responses to direct forest management activities of varying spatial extent?*
>
> *M4 Part 3) Which can and cannot be observed using SMA of MSS images?*

Figures 6-26, 6-28, and 6-30 through 6-35 answer the second question. Let me now address questions 1 and 2. From the analysis presented here, it appears that MSS resolution captures the grain of some human activities reasonably well in some instances and does poorly in others.

In general, the results show that forest disturbance (e.g., human timber cutting or natural storm disturbance) tends to result in an increased near-infrared reflectance as a result of higher levels of xeric vegetation. This supports the contention that recently cut areas, having higher concentrations of young trees, shallow rooting systems, less available water and more exposure to direct sunlight, will exhibit higher degrees of xeric leaf reflectance. Tract 70A, provides a particularly good example of the opposite, where a stand cut early in the time series, appears to be gradually losing its xeric-vegetation characteristics as time passes.

The sensitivity of MSS to commodity related human disturbance depends on the spatial and temporal extent of the disturbance and the spectral differences between the disturbance and its surroundings. For example, development activities may have a relatively small spatial extent but it has a longer temporal extent. The new development in the forest office complex is relatively small in spatial extent (3.3 acres) but it is longer in temporal extent (thus more likely the image sampling will pick up the disturbance). Since this is a disturbance that replaces a vegetated area with non vegetation substances (e.g., rooftops), the spectral change is distinctive and easy to identify, even if the disturbance spatially is relatively small. Similarly, forest cut areas referred to as "openings" were more likely to be recognized and identified in the time series than were areas subject to selection cutting.

Road construction and maintenance could be identified only when the roads were wide enough to leave the road uncovered by adjacent tree canopies. Four lane highways were readily identifiable. Two lanes throughout the forest area were sometimes recognizable and sometimes not. Interestingly, more roads were identifiable in the earliest (1972) scene, which suggests that images which capture recent 2 lane road development can be detected. The longer time passes from date of road construction, the more likely the road will not be detected due to canopy growth of nearby trees

Several additional methodological lessons were learned from this analysis. First, additional, supplementary information naturally improves MSS change detection. By having the luxury of a 1992 TM image, I was able to detect change locations in the MSS images more readily. The footprints of openings, cut many years prior to 1992, could often be visually identified in the 1992 TM scene and then identified in the MSS change maps. These areas were often represented in xeric endmember change maps in unsaturated colors (meaning their change was more subtle) which made it difficult to find without the complementary TM scene. The lesson here is obvious: the more supplementary information available the better change identification will be. Change detection projects would be wise to purchase one TM scene at the end of the time series which will both add to the time series and also help identify footprints of earlier change in MSS scenes. If TM scenes are unavailable, aerial photos would also be of great assistance.

Second, there are several costs and benefits in undertaking a spectral mixture analysis. The costs are additional effort. The analyst must convert the images to at-surface reflectance and then the additional work of identifying appropriate end members. Change analysis can be done with the classification maps generated from DNs or by generating color composites from individual band images for several time points that have been converted to at-surface reflectance. For example, in the case of MSS imagery, the analyst can overlay the Band 4 layers from each time point in one color composite to produce similar results to a color composite of the xeric end member fractions. Similarly, one could overlay Bands 1 or 2 from these images and produce similar change maps to one developed for the soil end member.

But the benefit SMA provides over the spectral change map method is that it combines all the band information from each scene to produce these fraction layers. The change maps produced are more striking visually than the similar composite produced using the image processed data. Moreover, SMA provides a way to develop standard measures based on endmember libraries that can be used for comparative purposes. This study has initiated such a spectral library for the south-central Indiana region (Figures 6-12 and 6-13). ASCII files with the available reflectance data for each band are available for other researchers to use.

Further, by utilizing endmember fractions, we can begin to develop landcover classification systems based on *physical measures*—reflectance—of the earth's surface[26]. We could, for example, classify a "mature forest" as one that comprises less than 40% xeric vegetation as shown by the mean value in the 1992 image in Figure 6-26. This common definition could then be utilized by another study investigating similar forest types.

Finally, the ability of SMA to provide sub pixel measurements—fractions—of land cover is more appropriate than standard classification maps when coarse resolution MSS images are being used. The land encompassed in 80 meter squared pixels will rarely be of one "pure" type. It will most often be a mix of several land cover types. SMA helps us identify what those types are instead of forcing the pixel to be represented in one category.

With all of these lessons learned articulated, what are the next steps in this analysis? Chapter 4 suggests that in Indiana, the incentive structure is such that higher level of timber harvesting will have taken place in state managed forests than in the National Forest. Chapter 4 also suggests that forest change trajectories will probably be different in several of the Hoosier management units because of their differing use designations over time. Chapter 7 will do a comparison of Hoosier National Forest Pleasant Run Unit and Yellowwood State Forest and will "scale up" from this individual location analysis to an analysis of entire physical landscapes under varying institutional landscape histories. A comparison of these two areas over time should reveal patterns that reflect the direct activities property managers are taking as a result of their incentive structures. Holding other things constant, I expect to see a higher level of xeric vegetation in the state properties when compared with similar landscape under federal control. National forest property should reveal a higher degree overall of mesic trajectories representing the "protected forest stands" in Figure 6-26. Chapter 7 will test these hypotheses. But we have to be careful. This chapter also taught us that comparisons will have to be done carefully.

Chapter 6 Endnotes

1. 80 meters squared is an approximation. It is actually 79 meters x 56 meters (Campbell, 1996).

2. Green (1998) provides a useful summary of literature on this topic

3. For example, an image taken in a winter scene might provide added information about woody biomass of a forest. A late summer scene however, when tree canopies are filled with leaves, provides more information on the breadth of the forest canopy, information a winter scene is not likely to provide.

4. A fourth image, 9/12/79 was dropped out because of problems in georeferencing.

5. Striping removal requires the images to be in the original satellite format in order to be detected. Georeferencing "rubbersheets" the image thus making striping removal most difficult.

6. A significant amount of work was dedicated to preprocessing this fourth MSS image not from the NALC dataset. It was taken on 9/12/79, and was destriped and georeferenced. Through this process I generated the destriping procedures provided in Appendix A and B. While the image passed the first two validation procedures, it failed the third.

7. I developed a standard spreadsheet for radiometric calibration and atmospheric correction of MSS images and figured out how to process MSS images supplied by organizations like NALC that do not supply the original header data. Calibration is conducted using parameters provided by Markham and Barker (1986). Using this method and the spreadsheet I developed with assistance from Glen Green, *any* MSS image can be calibrated. This is an important step for researchers planning to use and compare MSS images for human dimensions studies. Since I have done this several others at CIPEC have begun to use these methods I have developed on other projects in Central and South America.

8. For example, the atmospheric correction process conducted here utilizes the dark target approach (Chavez, 1988). This removes the additive effects of the atmosphere but not the multiplicative effects. This noise is therefore removed by radiometric rectification.

9. Much of my early effort in this dissertation was to develop spreadsheets to do these calculations. No remote sensing software package that I could find had a procedure to radiometrically calibrate MSS images. It seems that most companies are most interested in working with the newer TM technologies. Copies of the spreadsheets I created are presented in Appendix D.

10. I am indebted to the National Science Foundation and the Center for the Study of Institutions, Population and Environmental Change for supplying funds for the labor for this portion of the project. I am indebted to Matt Brown for his effort putting the mosaic

together.

11. I did attempt to model shade directly by creating an endmember based on the shade spectra provided in the Adams *et al.* (1995) study. The subsequent model, with the mesic endmember replaced by the shade endmember, performed very poorly.

12. This process is called "iterative linear unmixing" (ENVI, 1998) and helps to improve the fit of your model. It, like 3-D scatterplots, helps you identify the extreme or "pure" pixels that do best to explain the mixtures in all the other pixels of the image. The final xeric vegetation endmember was chosen using this technique.

13. The need to remove clouds and their shadow are obvious, however the reader may be questioning why water areas were removed. Given the three endmember limitation (# of bands - 1) to do linear unmixing, water bodies were removed so that one degree of freedom wasn't used up by having to model water spectra. A similar endmember analysis could be done where only water bodies were included in the analysis and a linear unmixing approach of water bodies only could be done modeling soil, water, and vegetation.

14. The 9/30/72 image was acquired at 10:55 am (local time), the 9/01/85 image was taken at 10:46 am, and the 9/28/92 image at 10:45 am. Source: Image header information.

15. In addition, agriculture areas in 1985 exhibit live vegetation, whereas most of the same fields in 1972 and 1992 have a soil or litter reflectance spectra. This adds credence to the water based argument: more moisture availability in the late summer when conditions become the driest appear to prolong the growing season.

16. Unfortunately, the best information available was the Indiana Geological Survey's *Geologic Map of the 1° x 2° Indianapolis Quadrangle, Indiana and Illinois, Showing Bedrock and Unconsolidated Deposits* at 1:250,000 scale and in non digital form.

17. A "tract" is the name utilized by the state foresters in the Indiana region to designate a management unit in their property. Tracts are often designated as a whole for a particular set of activities. For example, in Morgan-Monroe, several tracts are designated as a whole "old growth" forests and are therefore not subject to cutting activities.

18. This GIS coverage was created by Brenda Stein, Andy Swift and others responsible for GIS management at the Morgan-Monroe forest.

19. Classification maps are often used in remote sensing analysis in part because of the ease in which we humans can understand categorical data and maps. However, this means that we have to assign the continuous data to categories. Depending on the type of landscape, these categories may or may not be easily determined. In a study of a broad landscape with clearly defined physical and spectral boundaries between land cover types (e.g., a pasture and a quarry) classification may be easy to do. In landscapes such as this one, where we are interested in understanding fine spatial and spectral change between

vegetation that is very similar, a classification based analysis is much harder because determining appropriate classes may be more subjective or arbitrary. I am indebted to Glen Green for this point.

20. High contrast ratio of subpixel sized features (e.g., narrow roads through a wheat field) may bias pixel brightness values, thereby allowing the feature to be detected within an image with coarse spatial resolution.

21. This point hasn't been confirmed by the property manager. It is inferred from the trajectories.

22. It was not my intention to measure every cut location that had occurred within this public forest. Only a sample of cuts were taken based on what could be identified through the process just described. It was my intention, however, to get representative areas for the several types of cutting practices conducted in this region (e.g., group selection, single tree selection, etc.)

23. Often new sprouts of deciduous broad leaved trees are established on cut stumps. They coppice (Kimmons, 1992: 56). This activity then involves the maintenance of the environment around these seedlings to encourage their growth.

24. The exact mathematics: 500 Trees were planted in roughly a 85800 square feet area. This is equivalent to 7722 square meters. One MSS pixel is roughly 80 meters squared or 6400 square meters. 7722 square meters is .7722 hectares. To convert hectares to acres we multiply by 2.5, thus producing the result 1.9305 acres

25. For any given year, these three endmember percentages *should* add up to 1. Clearly in this location, the three endmembers don't fully explain the variation in the data for this region. Part of the reason that this soil, xeric and mesomorphic/shade model doesn't explain this areas very well could be because (1) there are other land cover that have a different spectra, and (2) shade isn't modeled very well. There is a fire tower in this site that may looks to have a very different spectra to the rest of the site. In addition, the small gaps for camping areas will tend to be shadowed when these images were taken. The sun, at around 9:30 am when these images were acquired, is relatively low in the south-eastern sky. The mesomorphic/shade end member probably is not capturing this phenomenon very well. It is a limitation in using MSS. TM, with its added bands, can have a separate endmember just to model shade (see, for example, Adams, *et al.* 1995).

26. See Adams, *et al.* (1995) for an excellent example of this technique.

Table 6-1: Sources of Variability in a Time Series of Satellite Images and their Solution

Year to Year Climatic Variability	Step 1, Image sampling
Seasonal Variability	Step 1, Image sampling
Diurnal variability	Landsat's sun synchronous orbit takes care of variability due to change in light due to time of day. All images are taken at approximately the same time each day.
Atmospheric Variability	Step 4, Atmospheric correction
Satellite produced variability	Step 2, Image Preprocessing Step 3, Radiometric Calibration; Step 5, Radiometric Rectification
Natural and human produced land cover variability	This is what we are interested in!

Table 6-2: Endmember "Reflectance Spectral Library" for Deciduous Forests in South-Central Indiana

Endmember	Percent reflectance in MSS Band 1 (green) .5-.6 µm	Percent reflectance in MSS Band 2 (red) .6-.7 µm	Percent reflectance in MSS Band 3 (near infrared) .7-.8 µm	Percent reflectance in MSS Band 4 (near infrared) .8-1.1 µm
Soil	.082667	.094667	.098667	.140667
Xeric Vegetation	.114	.098	.312	.51
Mesic Vegetation	066316	.051474	.136105	219579

Table 6-3 Summary of Human Activities Investigated in this Study

Preservation Related Activities:

- Forested areas of different age classes allowed to naturally regenerate

Commodity Related Activities:

- Road construction and maintenance (permanent roads and logging roads)
- Forest conversion for development purposes
- Silvicultural Activities
  - Group selection cuts
  - Single tree selection cuts
  - Timber stand improvement (TSI)
  - Planting

Recreation Related Activities:

- Campground construction and maintenance
- Trail creation and maintenance
- Areas where hunting is prohibited/permitted

Figure 6-1: Leaf Structure and Leaf Reflectance
(Adapted from Campbell, 1996: 462)

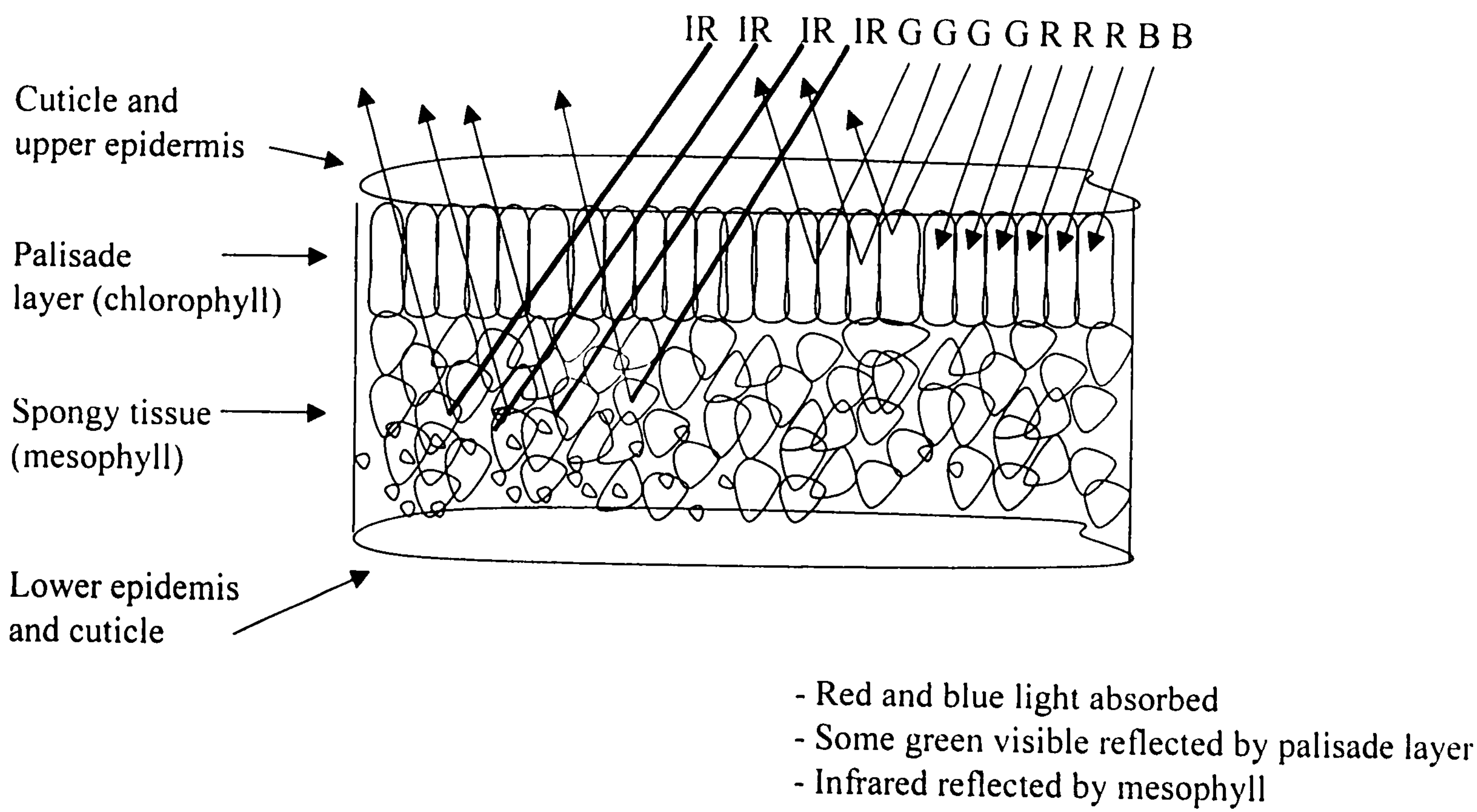


Figure 6-2: Summary of Image Processing and Analysis Steps

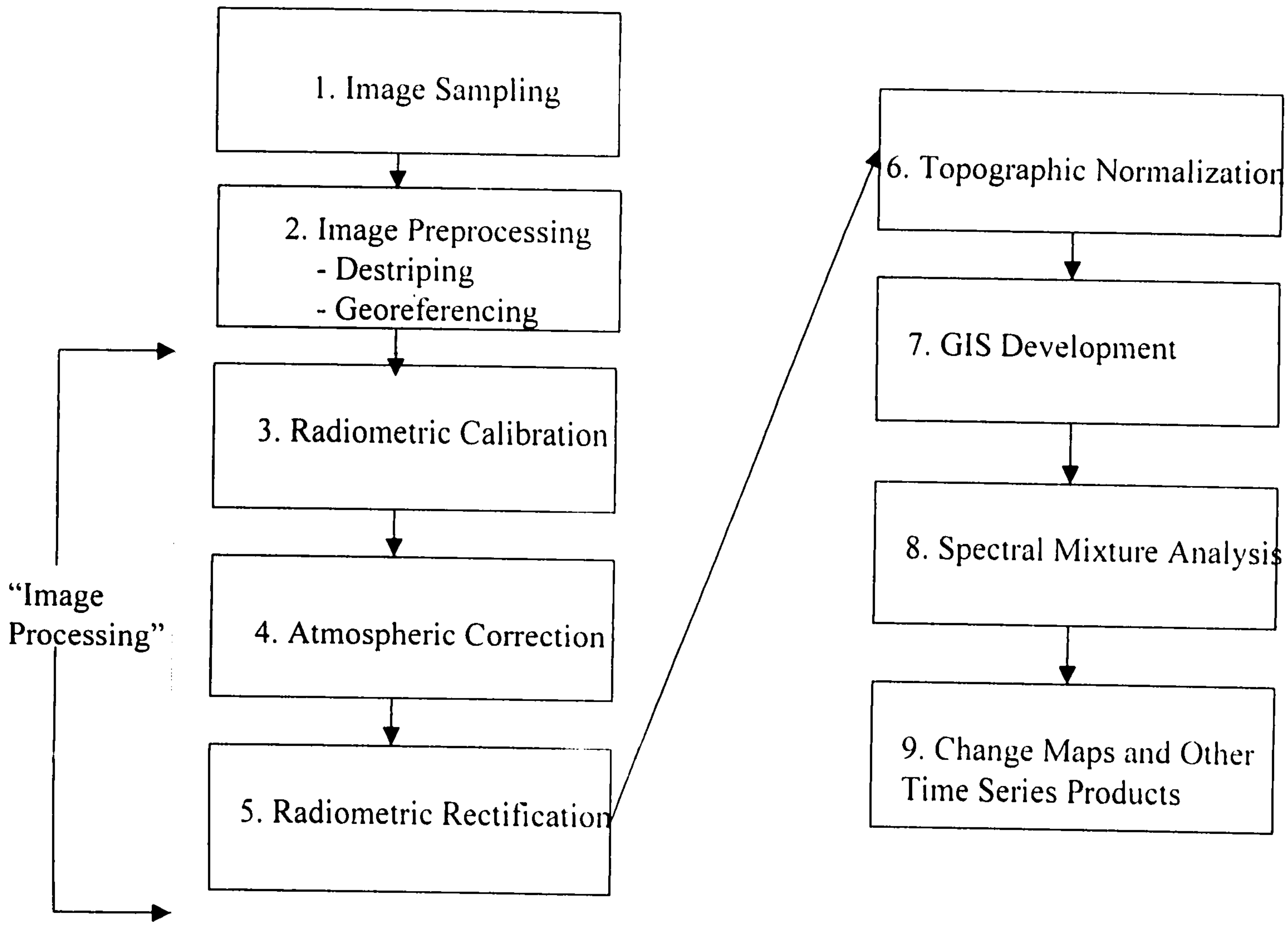


Figure 6-3: The Concept of Sampling "Critically"
(From Siegal and Gillespie, 1980: 151)

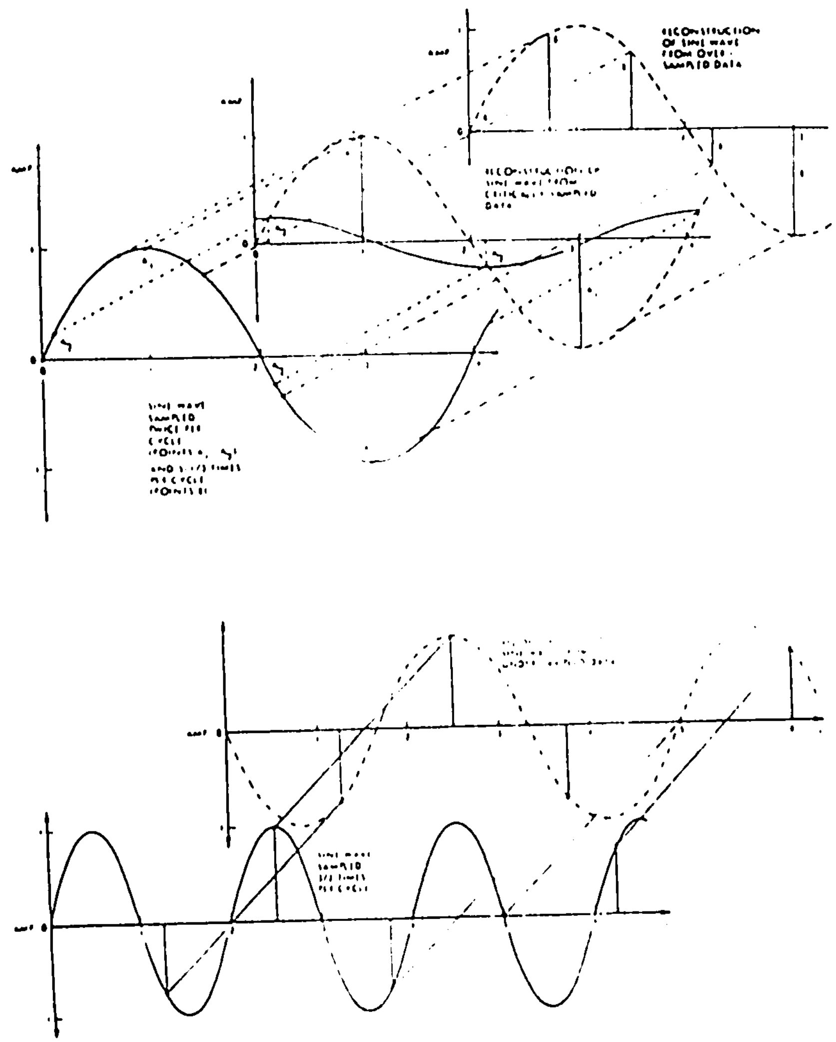


Figure 6-4 A: Verification of Radiometric Calibration, Atmospheric Correction and Radiometric Rectification Procedures--Mean At-Surface Reflectance Values for Consistent Dark Targets

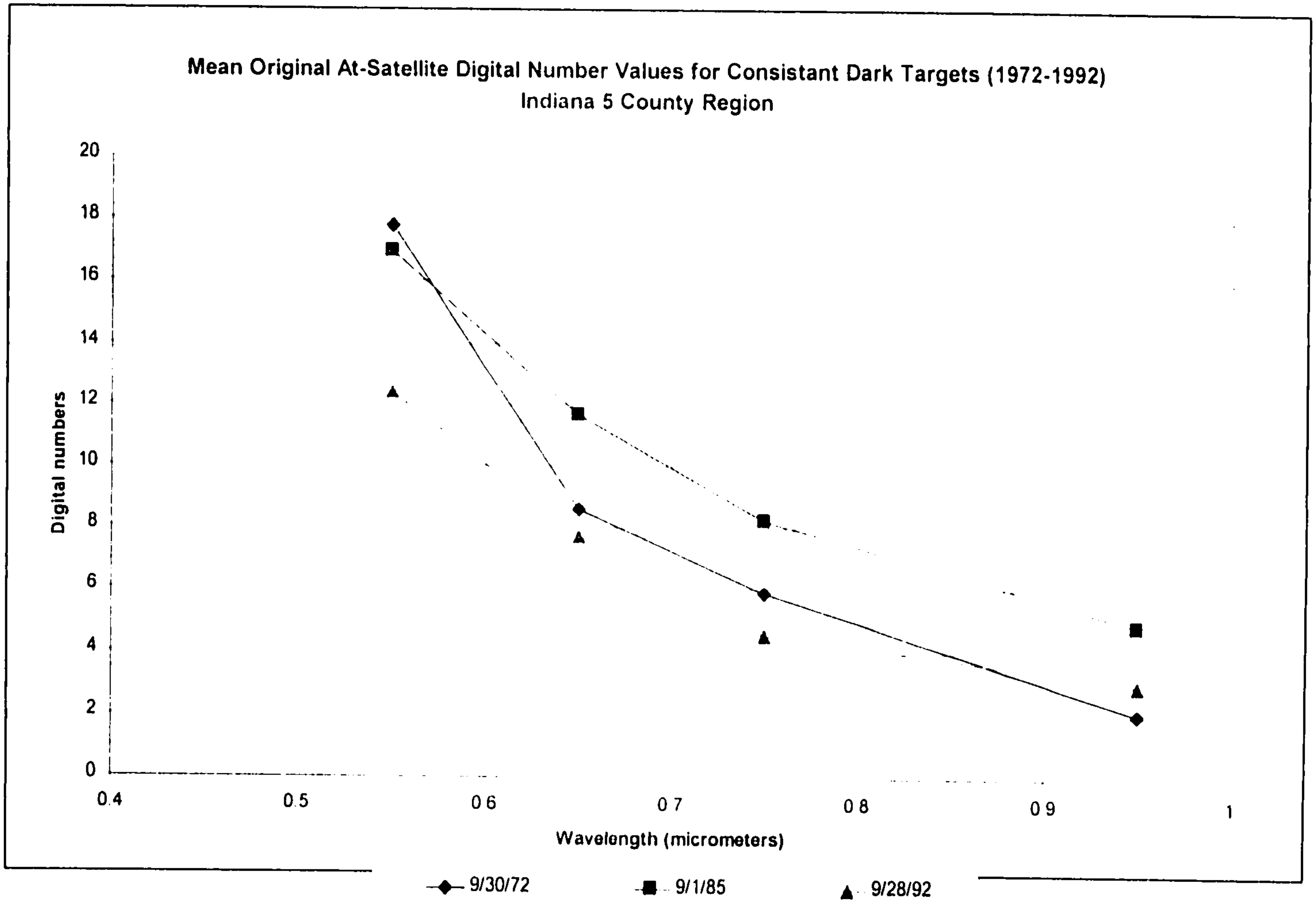


Figure 6-4 B: Verification of Radiometric Calibration, Atmospheric Correction and Radiometric Rectification Procedures--Mean Surface Reflectance Values for Consistent Dark Targets

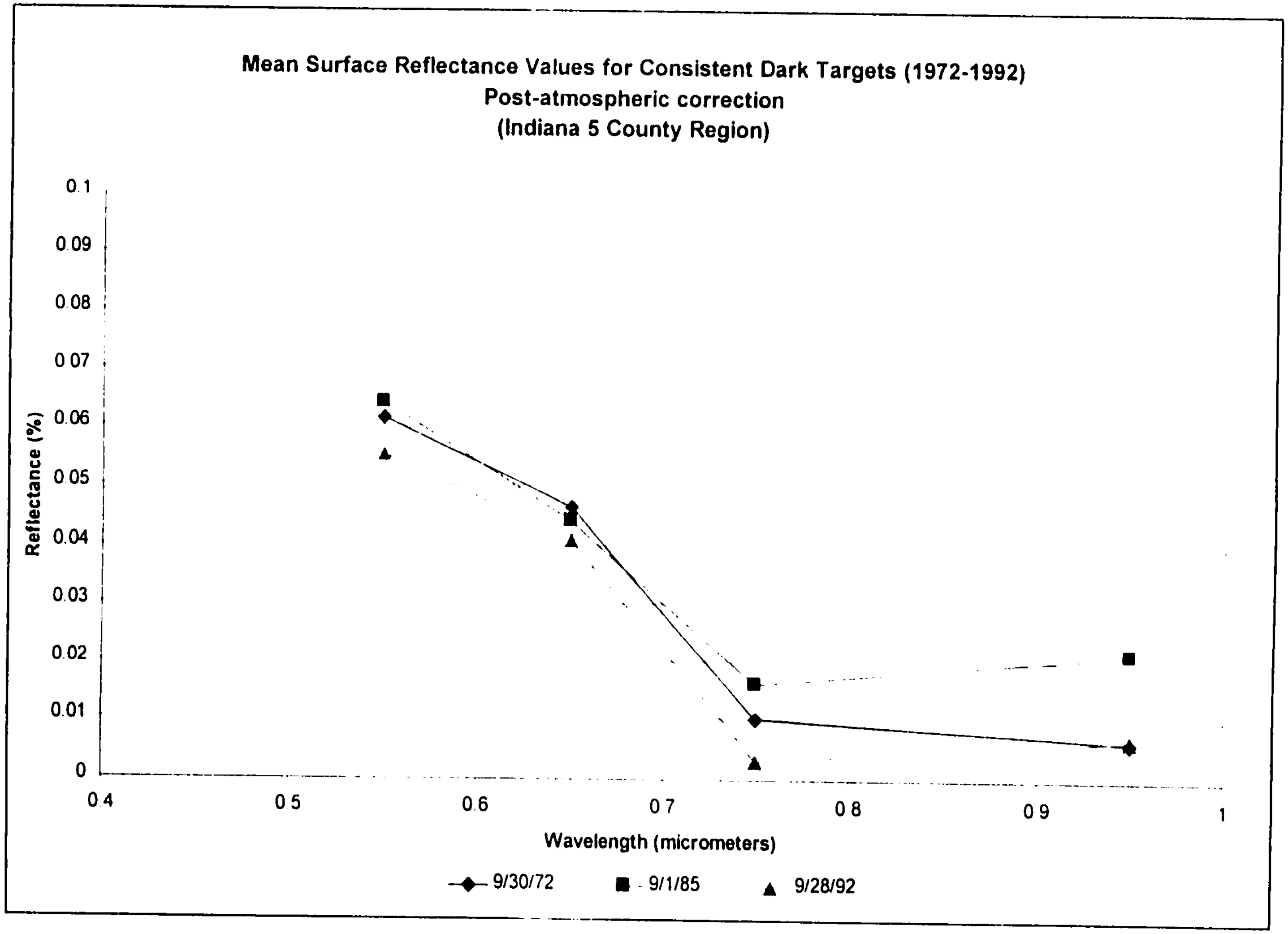


Figure 6-4 C: Verification of Radiometric Calibration, Atmospheric Correction and Radiometric Rectification Procedures--Mean Surface Reflectance Values for Consistent Dark Targets

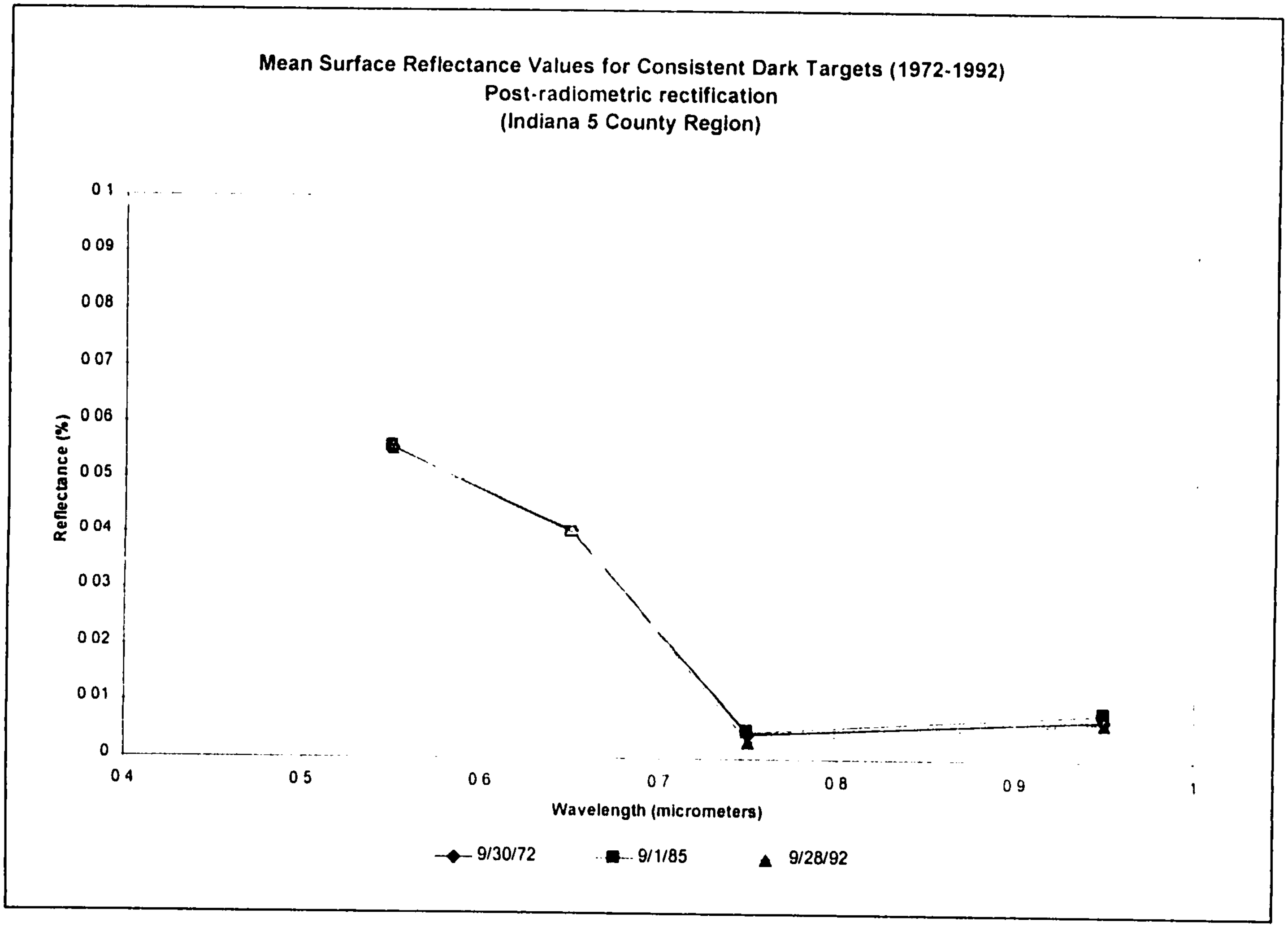
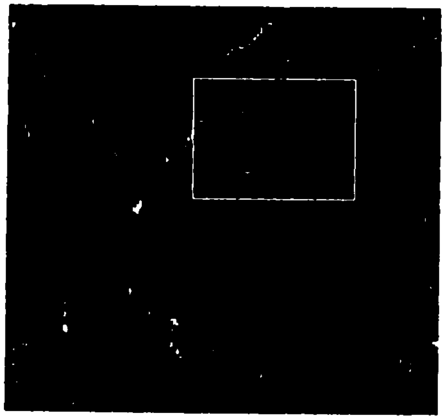
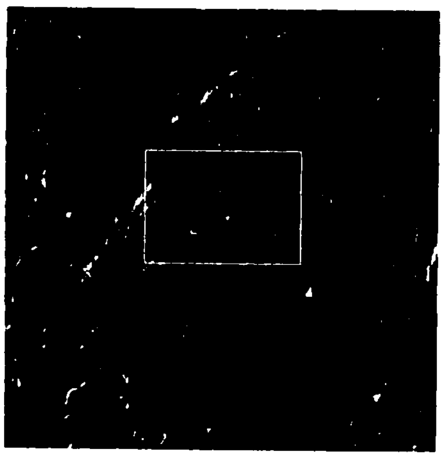


Figure 6-5: Verification of Topographic Normalization

A) 9/28/92 MSS Pre-topographic Normalization



B) 9/28/92 MSS Post-topographic Normalization



C) Verification Site Spectra

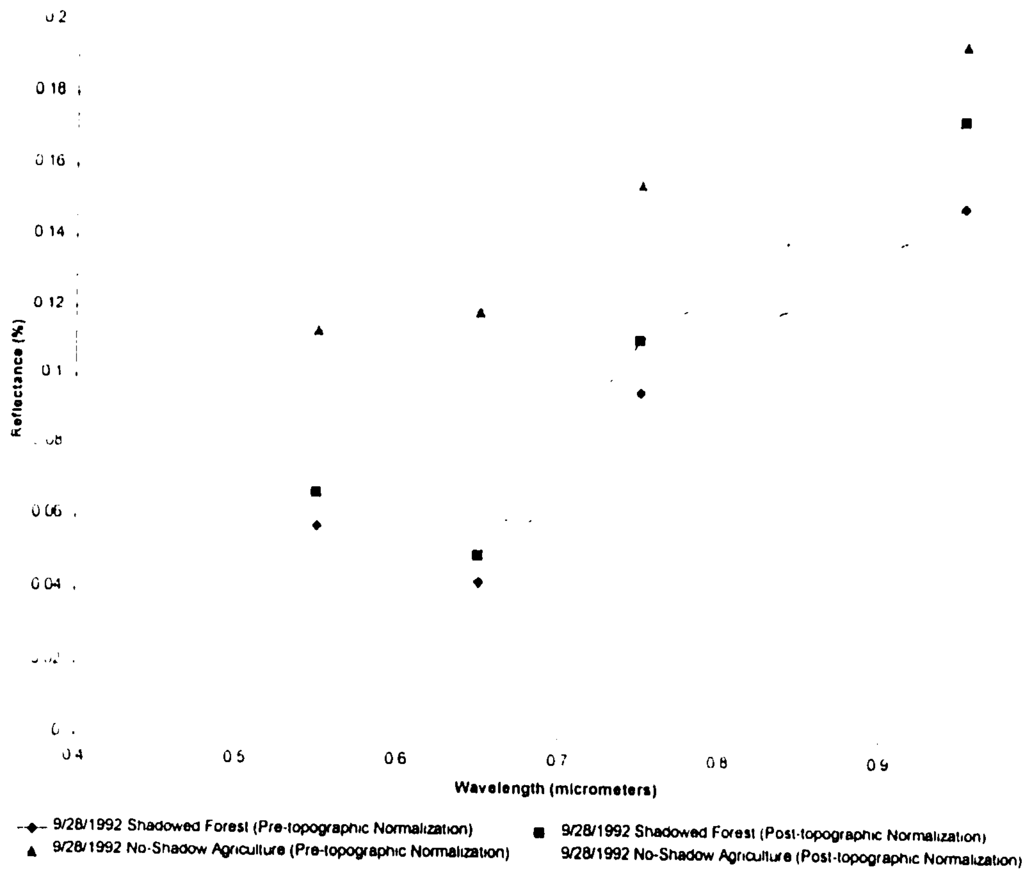


Figure 6-6: 9/30/72 MSS Image

Portion of Morgan-Monroe State Forest's Boundary Identified

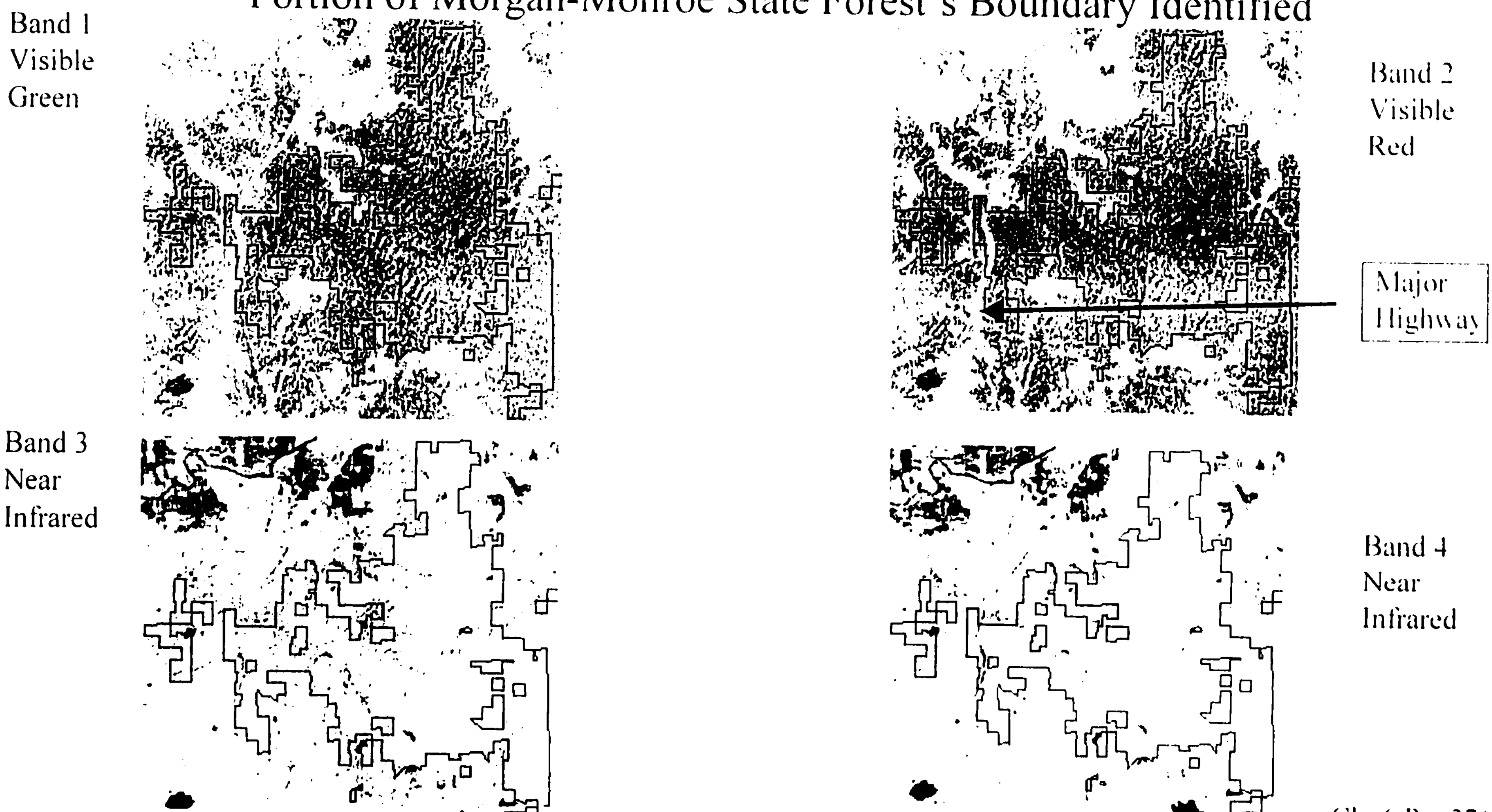


Figure 6-7: 9/01/85 MSS Image
Portion of Morgan-Monroe State Forest's Boundary Identified

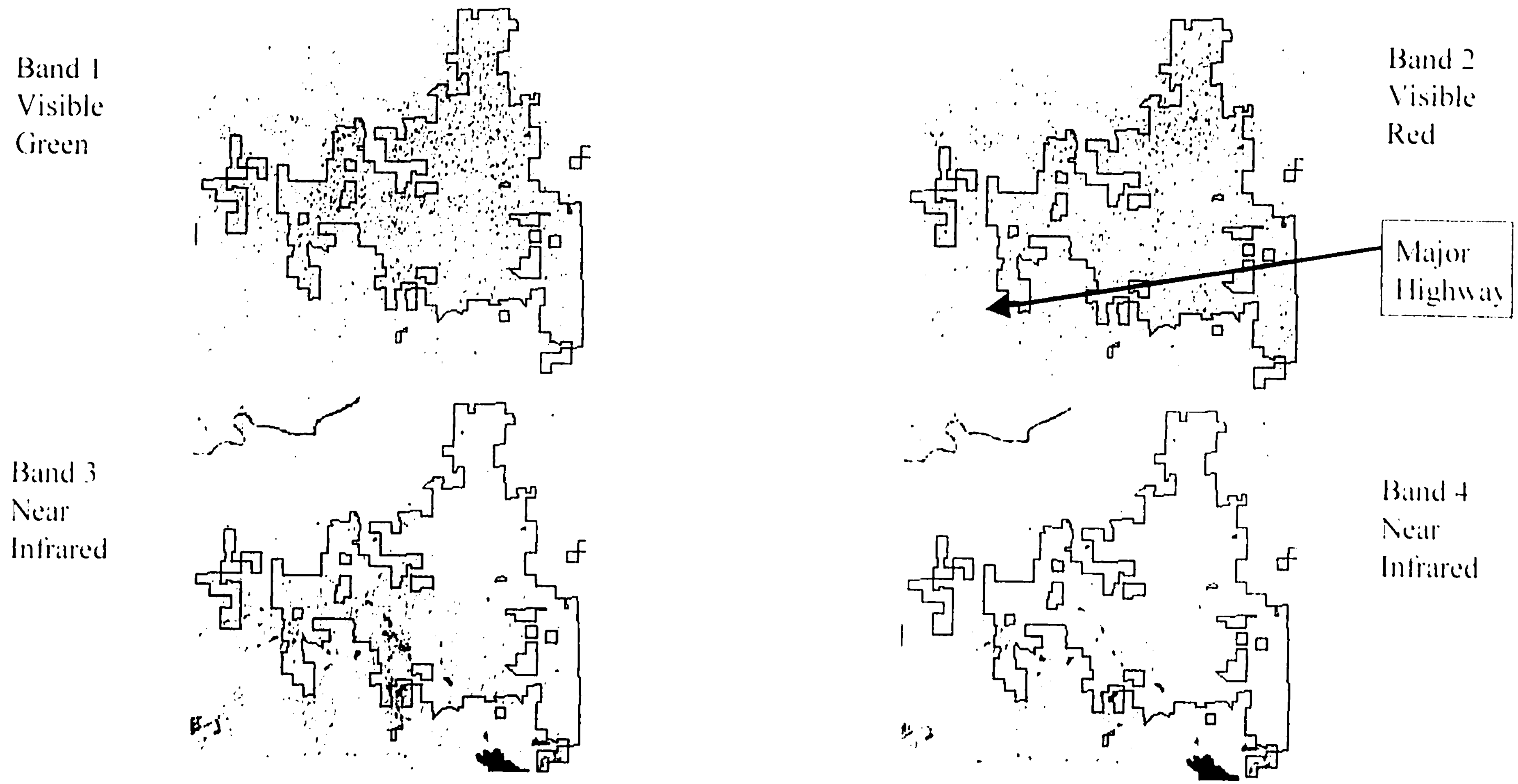


Figure 6-8: 9/28/92 MSS Image
Portion of Morgan-Monroe State Forest's Boundary Identified

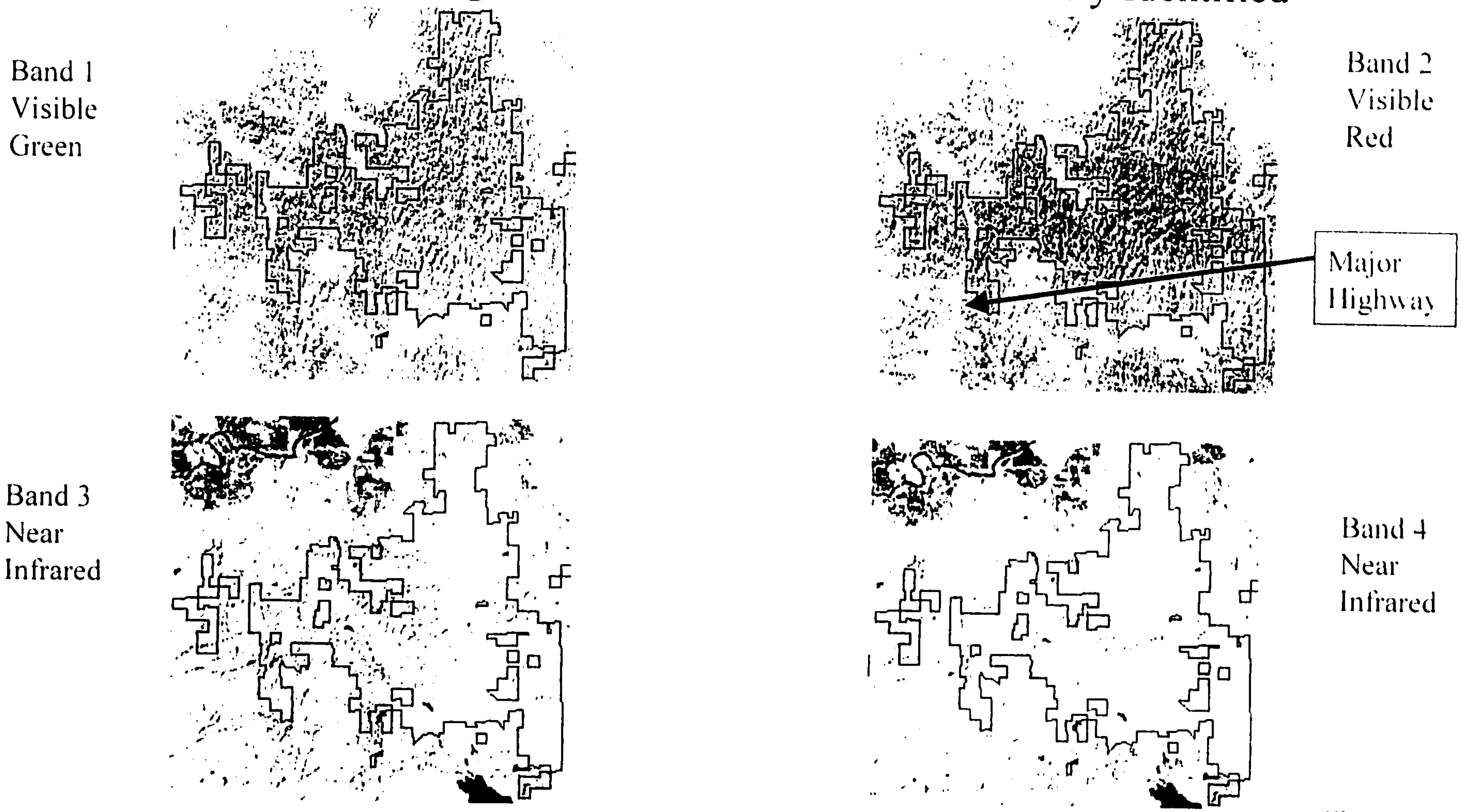
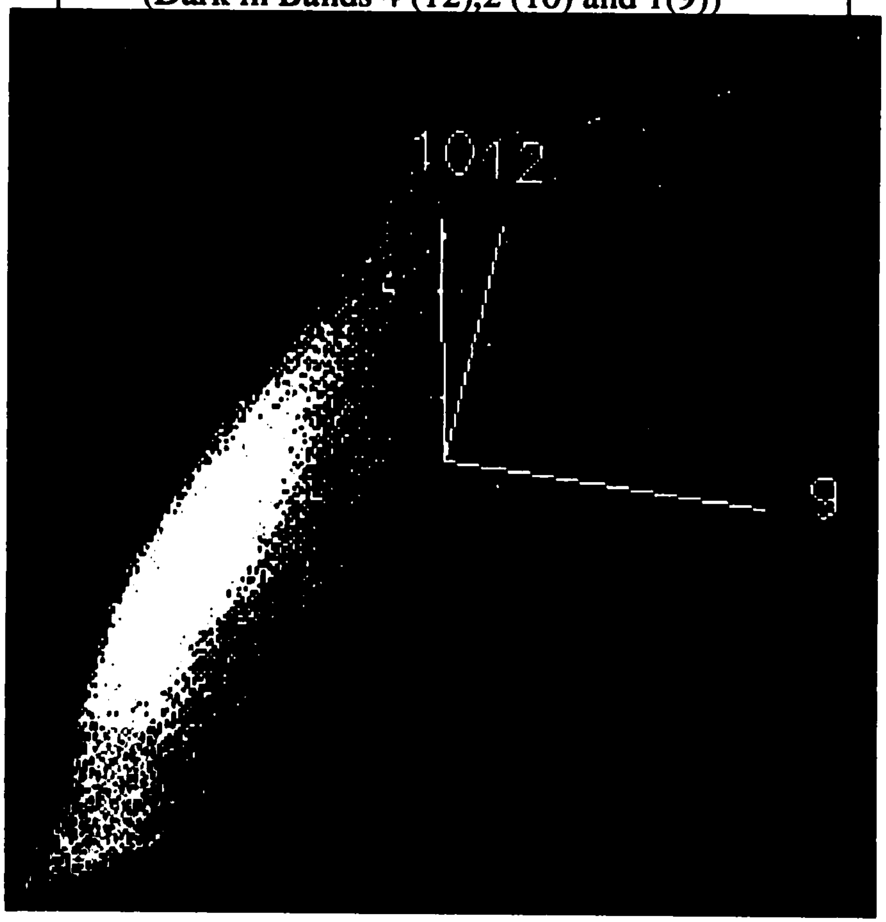


Figure 6-9: Endmember Identification using 3-D Scatterplots Removal of Water pixels (dark in Bands 1, 2 and 4)

Scatterplot of 1992 Full Public Forest Image (Dark in Bands 4 (12),2 (10) and 1(9))



Portion of the 9/28/92 Public Forest Image (R4, G2, B1)

Dark Water Areas Identified and Removed

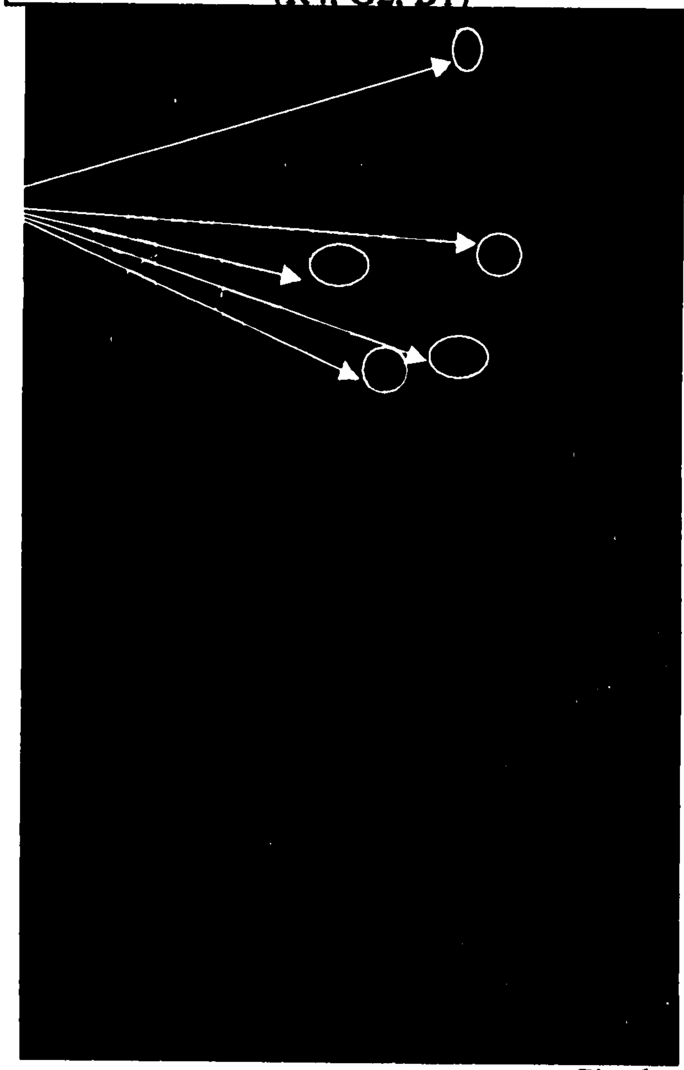


Figure 6-11: Example of Field Verification for Soil Site #3: Exposed Soil in an Open Agriculture Field
Longitude: 39° 20' 58", Latitude: 86° 27' 37"
Example of how Differential Global Positioning Systems (DGPS) was used to verify location
(If printed in color, the uncorrected points are in green, the differentially corrected point is in brown)

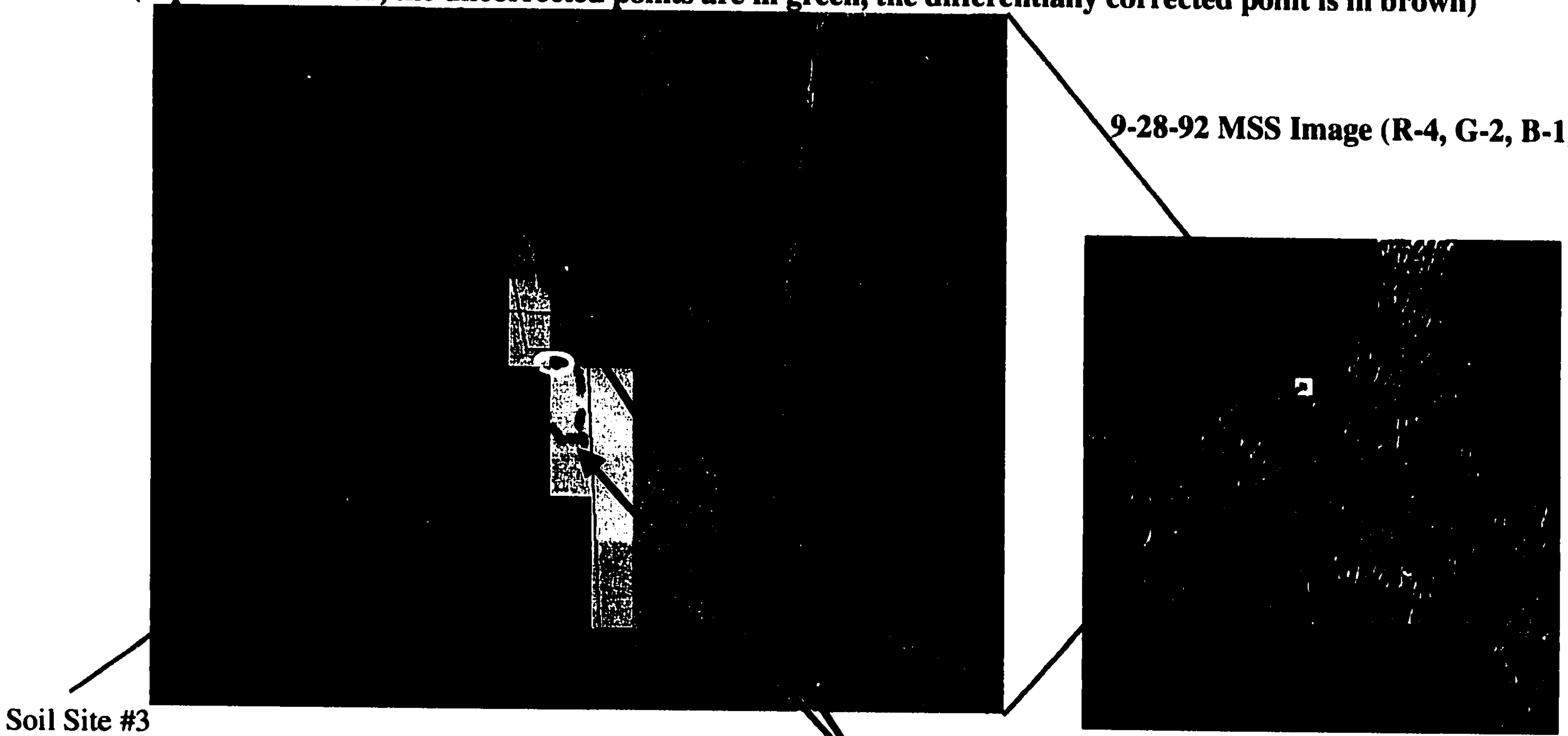


Figure 6-12: "Stick" Spectra of All Endmember Candidates

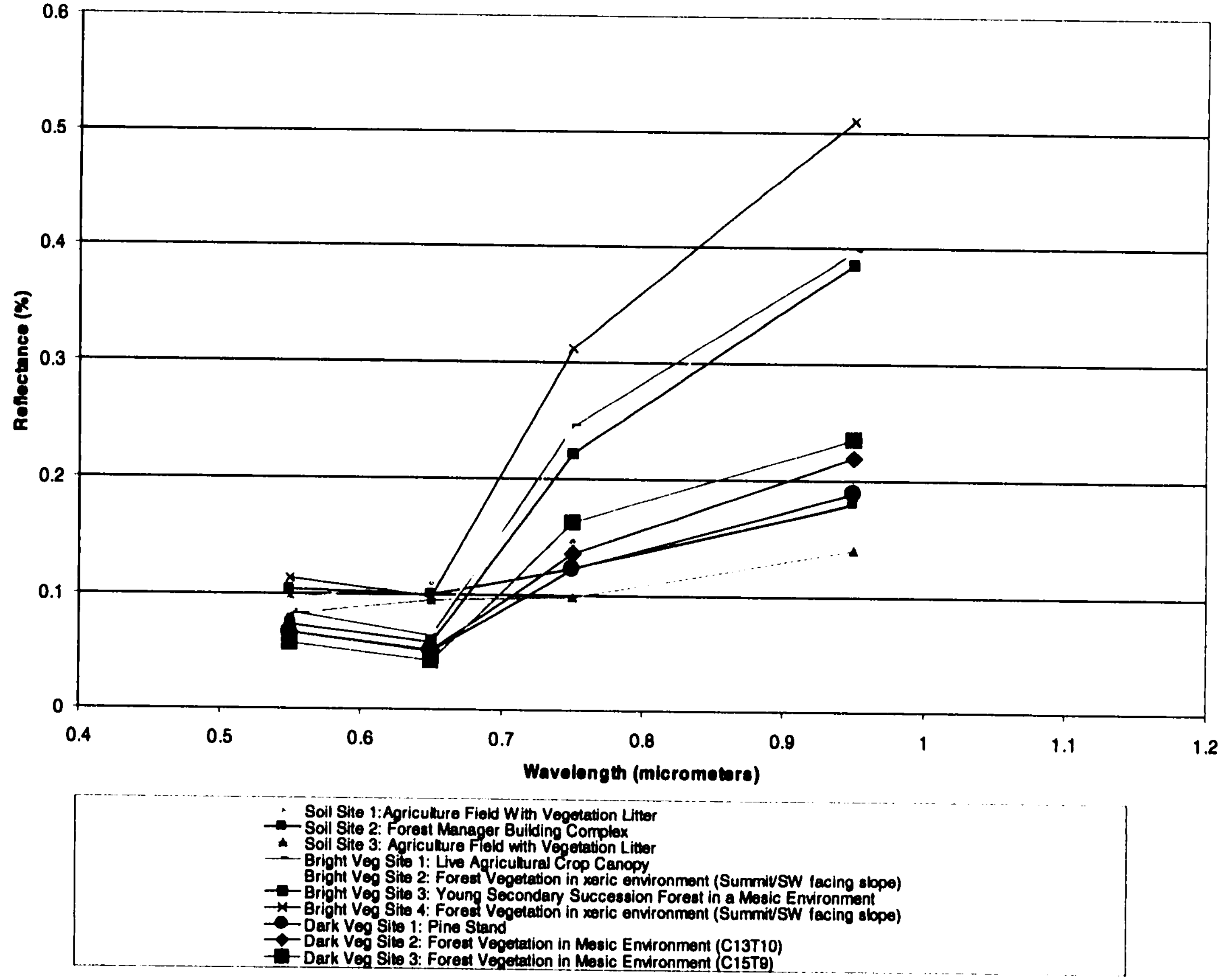


Figure 6-13: Stick Spectra of Chosen Endmembers:
(1) Soil, (2) Bright (Xeric) Vegetation, (3) Dark (Mesic) Vegetation and Shade

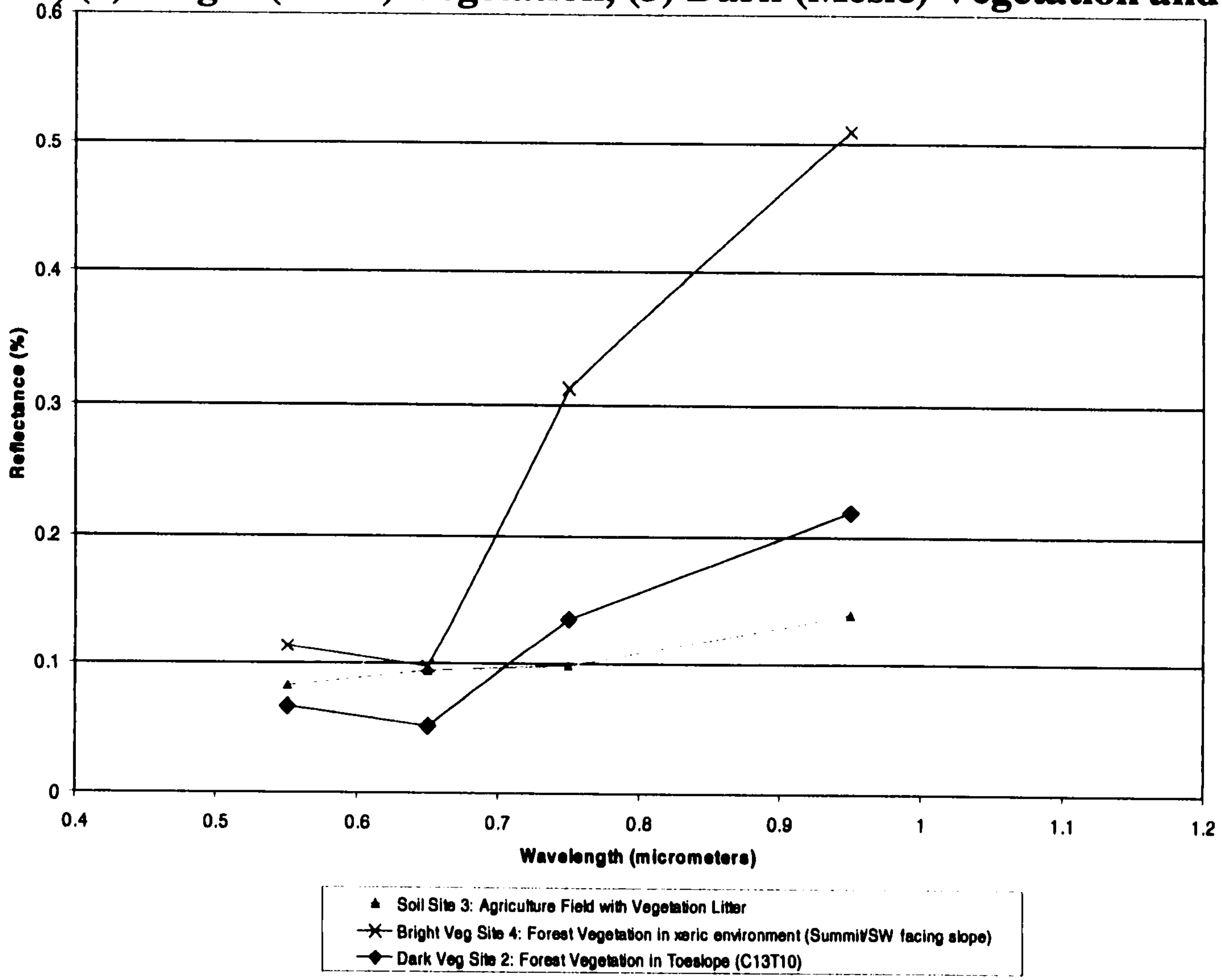


Figure 6-14: SMA Model 2 Results for a Portion of the 9/30/72 Image
(Bright white-high percentage, Dark-low percentage)

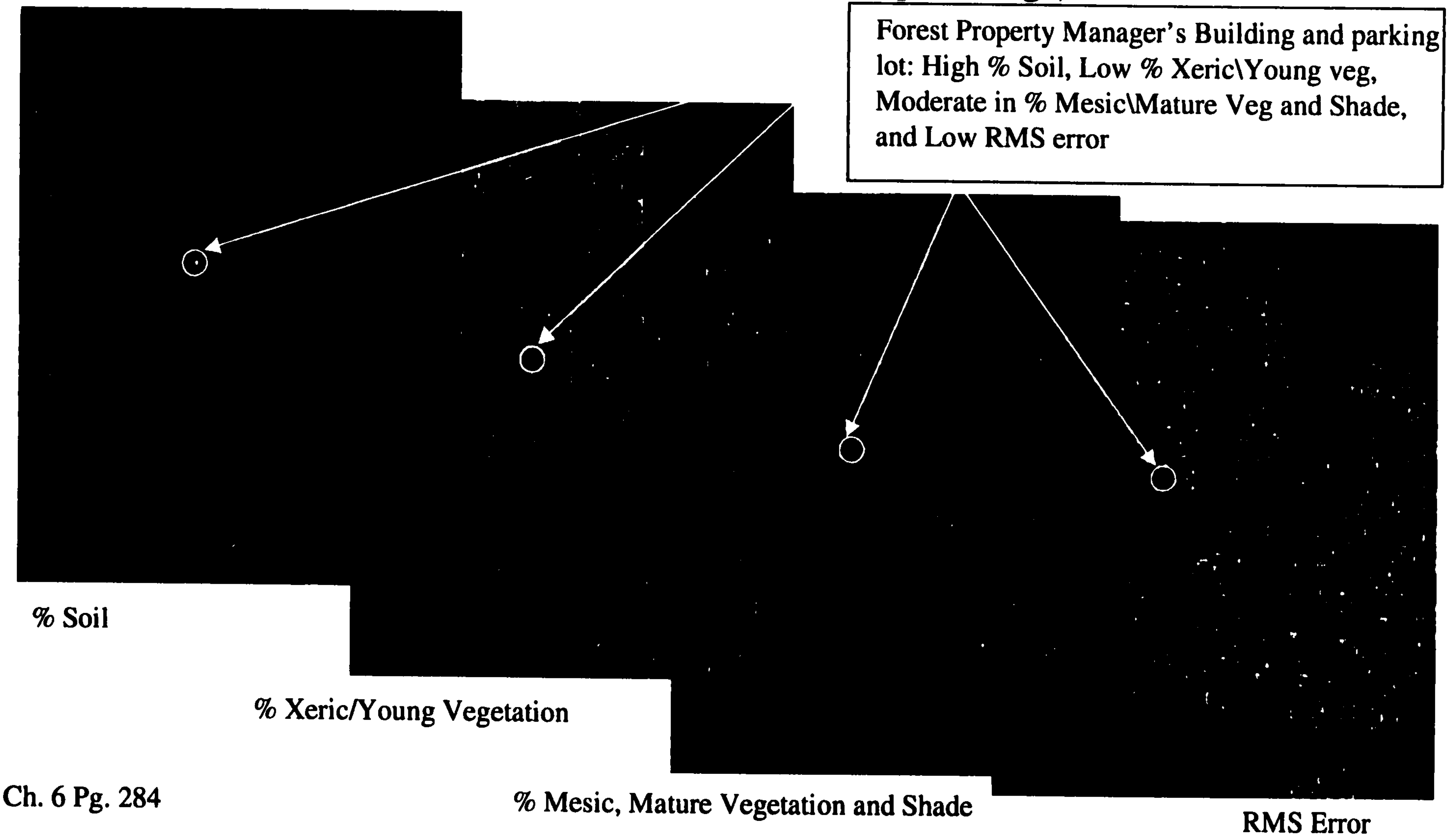


Figure 6-16: SMA Model 2 Results for a Portion of the 9/28/92 Image (Bright white-high percentage, Dark-low percentage)

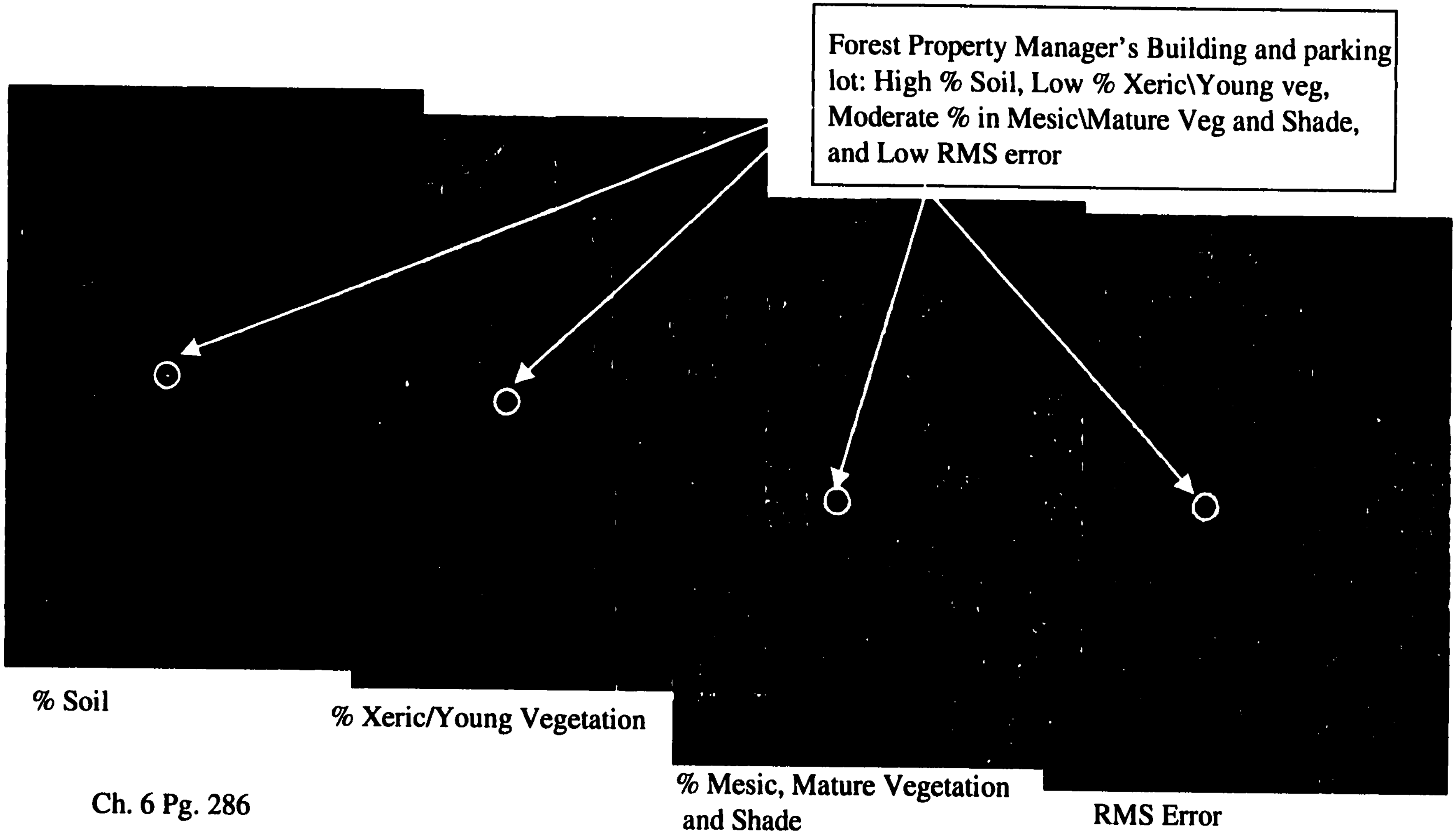
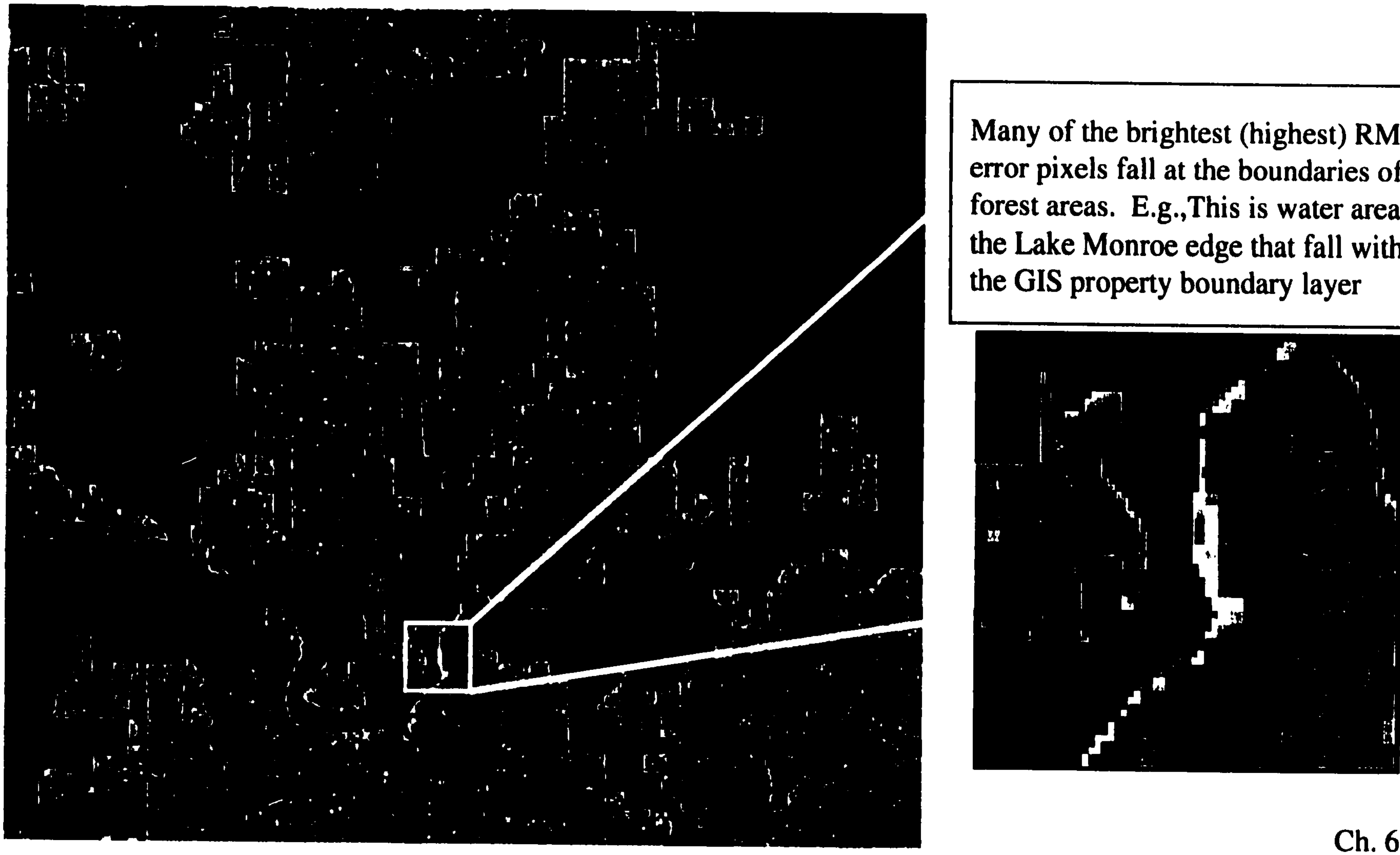


Figure 6-17: SMA (Linear Unmixing) Model 2 Results for 9/28/92 Image (Root Mean Square Error Image)

Portion of the 9/28/92 RMS Image



Many of the brightest (highest) RMS error pixels fall at the boundaries of public forest areas. E.g.,This is water areas from the Lake Monroe edge that fall within the GIS property boundary layer

Figure 6-18:Infrared Brightness Differences Between Valley Bottoms and Summits (after removing much of the shading effects due to topography) Portion of Morgan-Monroe State Forest, 9/30/72 MSS Band 4

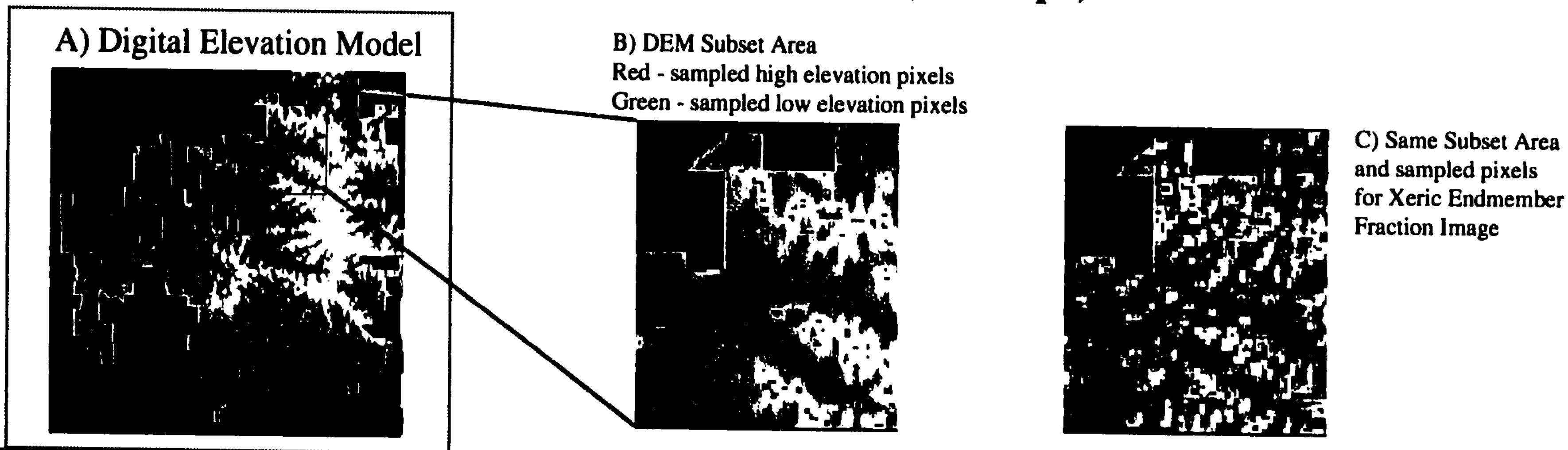
There is a distinct infrared brightness difference between xeric (dry) environments and mesic(wet) environments.

Summit and south east facing slopes are brighter in infrared reflectance than valley bottoms.

A) Bright summit (xeric) area

B) Dark (mesic) valley area

Figure 6-19: Difference in Means Test For 9/30/72 Xeric Endmember in High Elevation (summit) and Low Elevation (Toeslope) Areas



D) Difference in Means Test Results

μ_{S72} : Mean of high elevation (summit) pixels in sub-sample area, 9/30/72 (Red pixels)

μ_{T72} : Mean of low elevation (toeslope) pixels in sub-sample area, 9/30/72 (Green pixels)

H0: $\mu_{S72} <= \mu_{T72}$

H1: $\mu_{S72} > \mu_{T72}$

	High Elevation Pixels	Low Elevation Pixels
N	281 pixels	275 pixels
–	.5219	.2963
s	.0973	.1181

$s_p = .1080$

$t = 2.08$

$P < .025$

One-sided 95% Confidence Interval = .0479

Conclusion: with 95% confidence, the average percent of the xeric endmember in high (summit) elevations exceeds that of low elevation (toeslope) areas by 5 pecent.

Figure 6-20:Side-by-Side Comparison of Band 4 (Near Infra-red) Portion of Morgan-Monroe State Forest (1972, 1985, 1992)

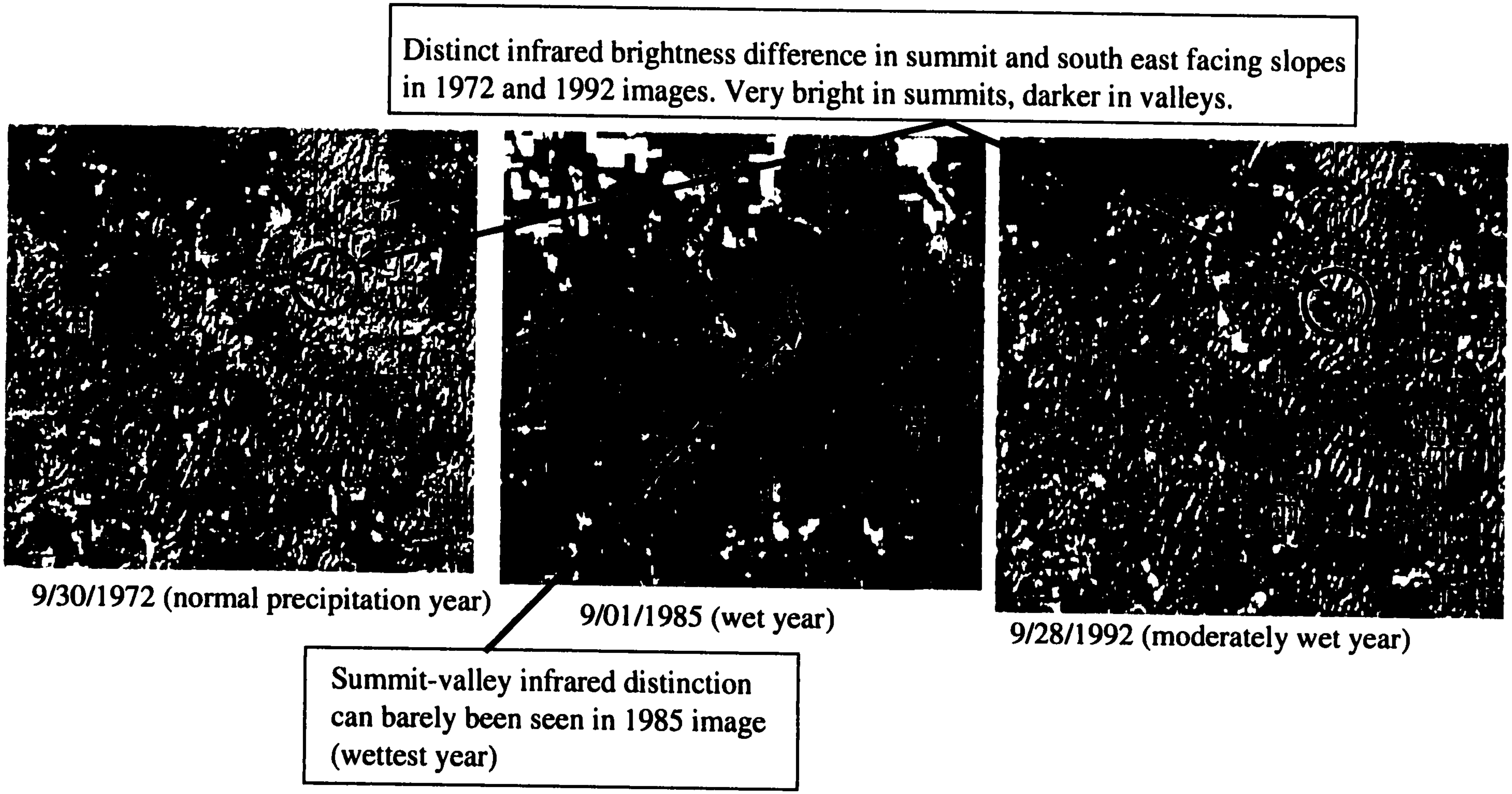
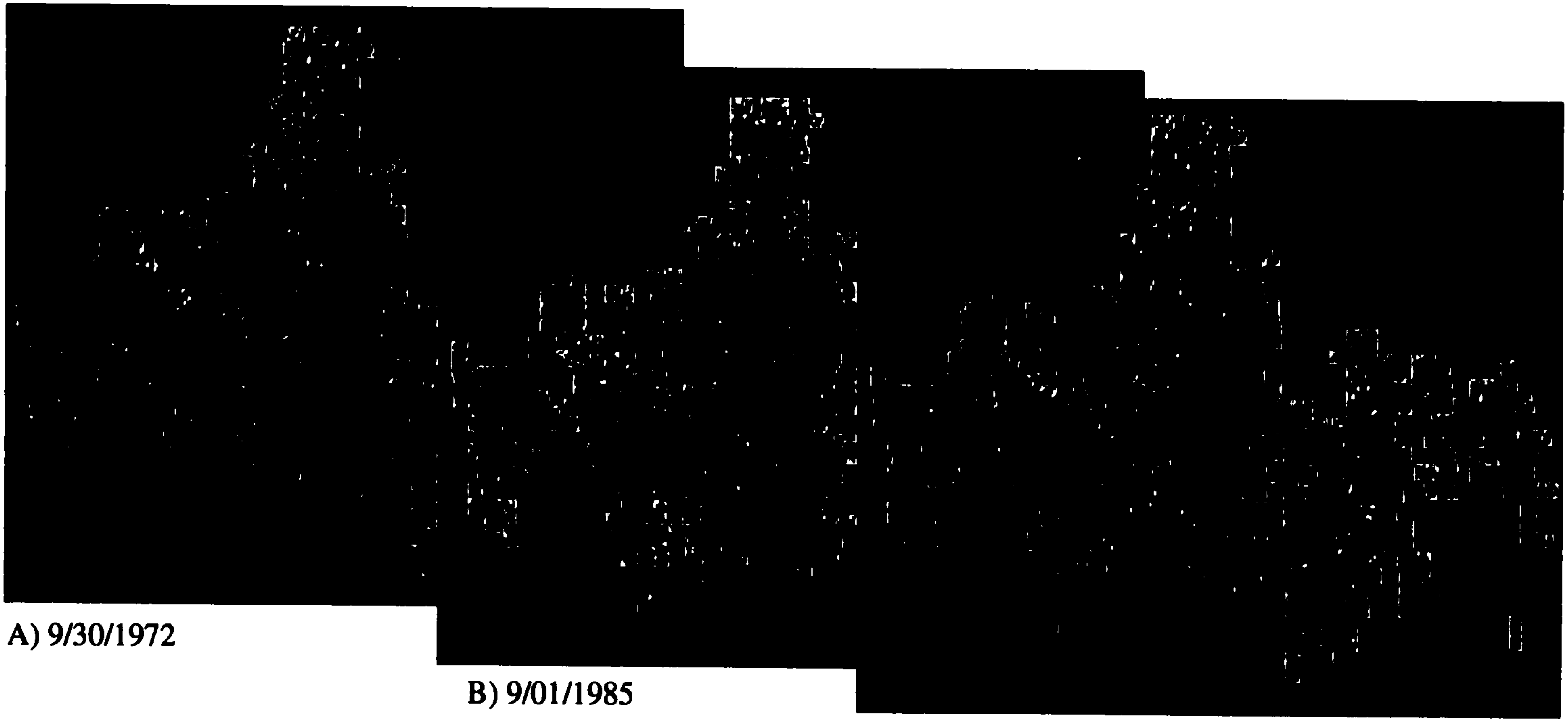


Figure 6-21: Side-by-Side Comparison of Xeric Endmember Fraction
Morgan-Monroe State Forest (1972, 1985, 1992)



A) 9/30/1972

B) 9/01/1985

C) 9/28/1992

Figure 6-22:

Annual Total Precipitation for Indianapolis Region 1970-1992

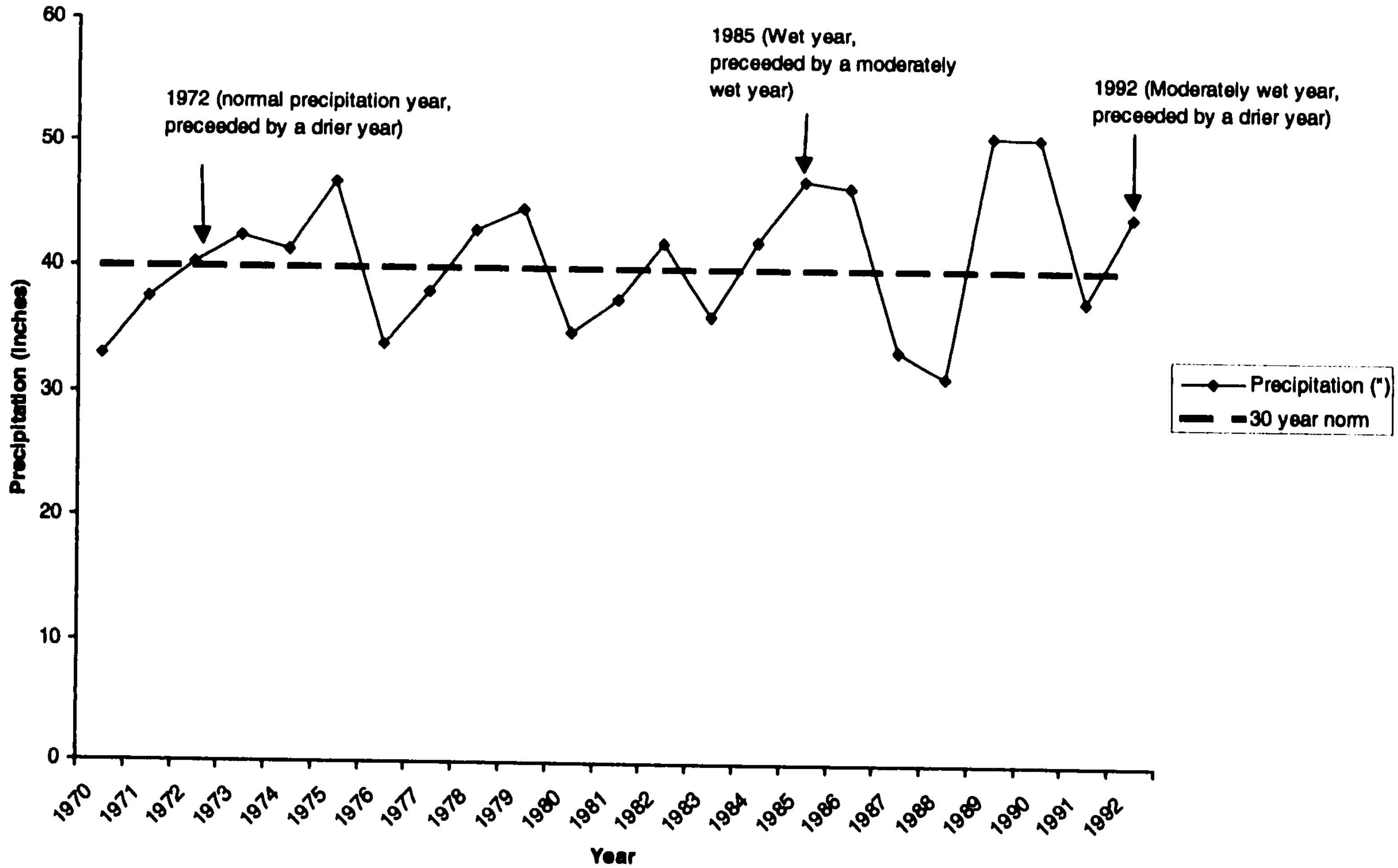
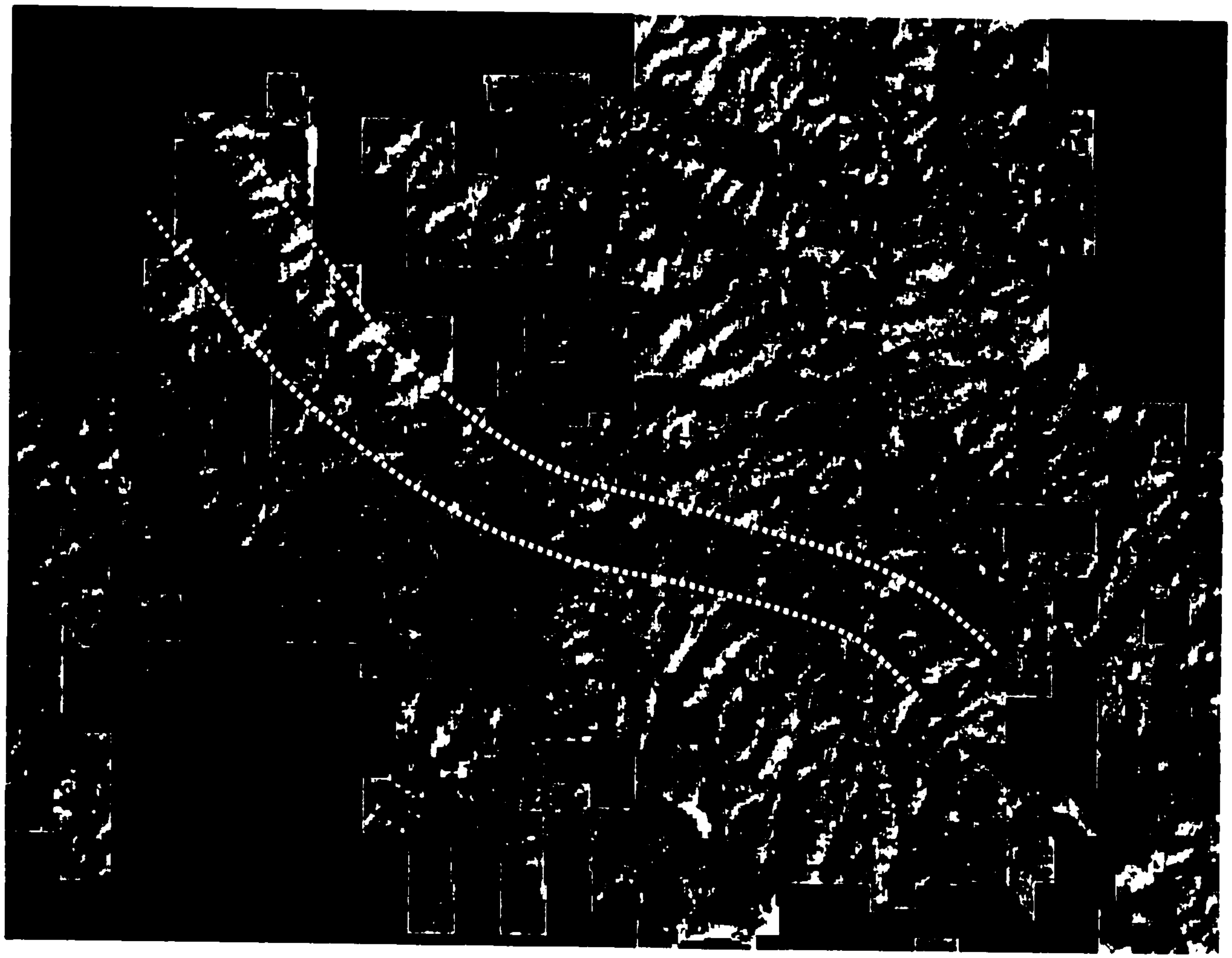


Figure 6-23: Identification of Mount Carmel Fault in Morgan-Monroe Forest (9/28/97 Landsat TM R-4, G-5, B-7)



Fault appears to lay in the area between the two white lines.

This fault line is interpreted from the 1:250,000 geologic map of the region and appears quite distinctive in color composites of both TM and MSS images.

Figure 6-24: Xeric Vegetation Multitemporal Fraction Image
(Red=9/28/92, Green=9/01/85, Blue=9/3072)

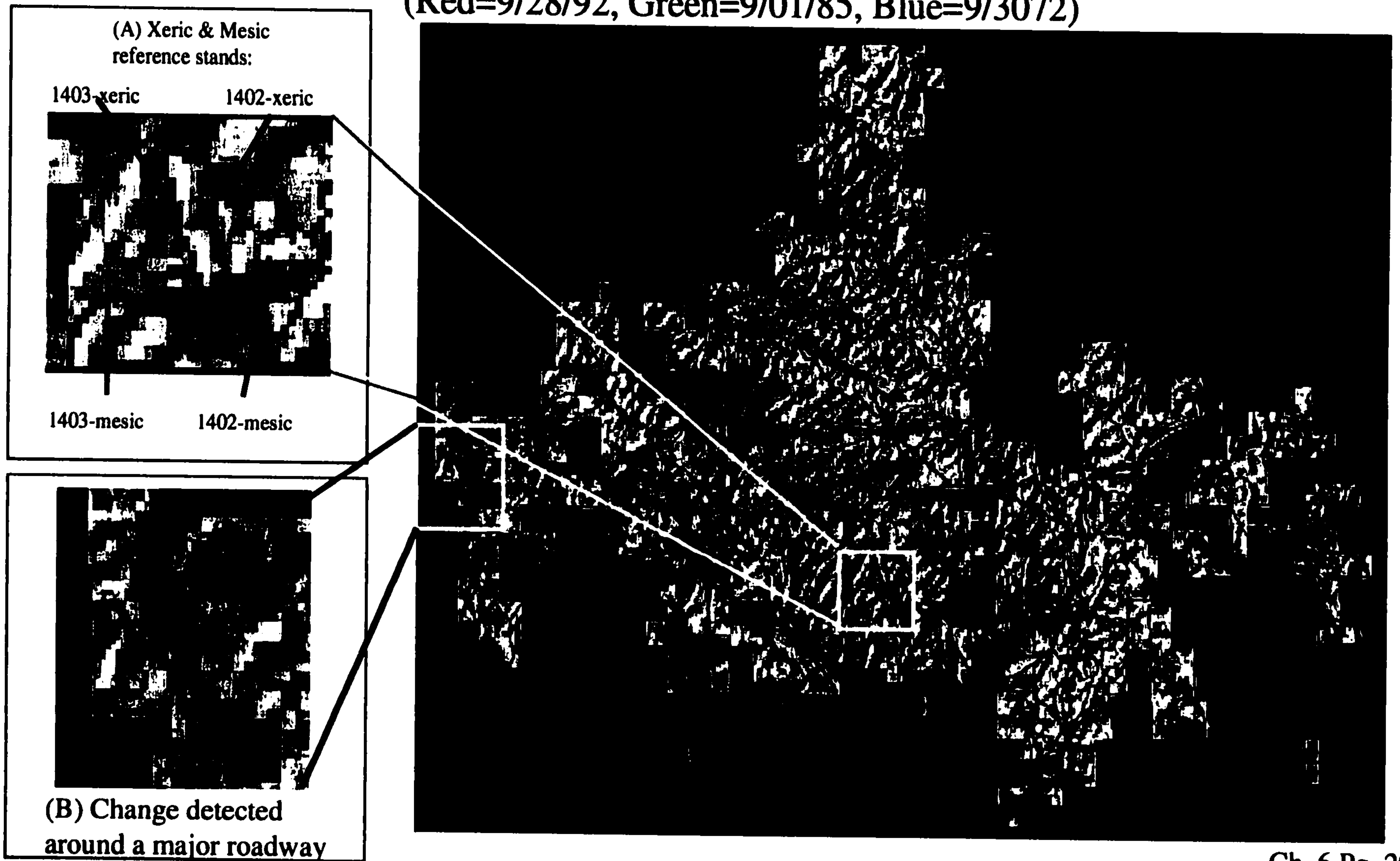
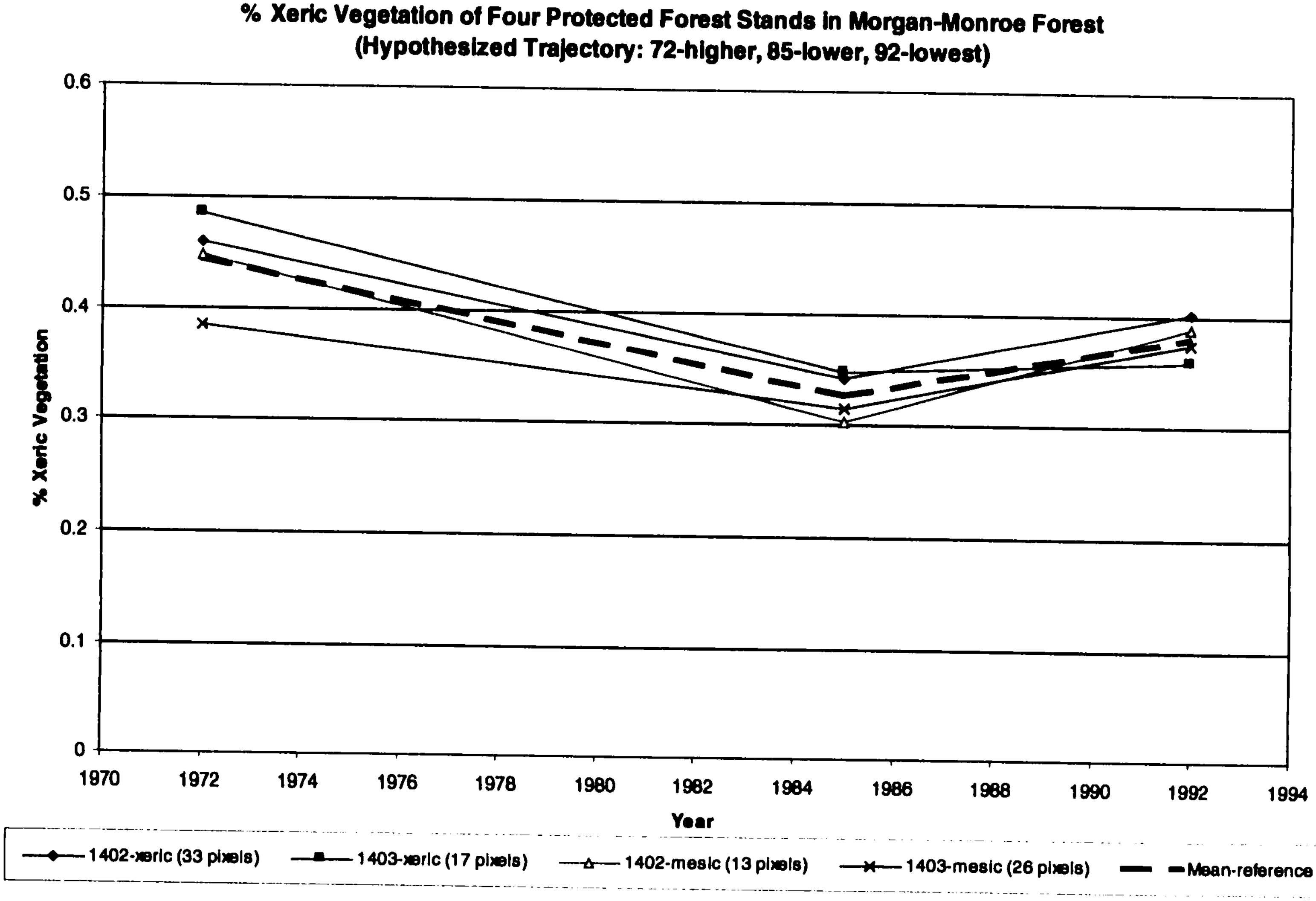


Figure 6-25: Interpretive Color Key For Multitemporal Fraction Images

(Adapted from Adams *et al.*, 1995: 145)

Color	Interpretation
White	High % in all years
	Moderate % in all years
Black	Low % in all years
	Low % in 1972 and 1985, High % in 1992
	Low % in 1972, High % in 1985, Low % in 1992
	High % in 1972, Low % in 1985, 1992
Yellow	Low % in 1972, High % in 1985 and 1992
	High % in 1972, Low % in 1985, High % in 1992
	High % in 1972, High % in 1985, Low % in 1992

Figure 6-26:



% Xeric Vegetation of Four Protected Forest Stands in Morgan-Monroe Forest
(Hypothesized Trajectory: 72-higher, 85-lower, 92-lowest)
% Xeric Vegetation
0.6
0.5
0.4
0.3
0.2
0.1
0
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
Year
1402-xeric (33 pixels)
1403-xeric (17 pixels)
1402-mesic (13 pixels)
1403-mesic (26 pixels)
Mean-reference

Figure 6-27: Road/Construction Detection Using Soil Multitemporal Fraction Image:

Red=9/28/92, Green=9/01/85, Blue=9/3072

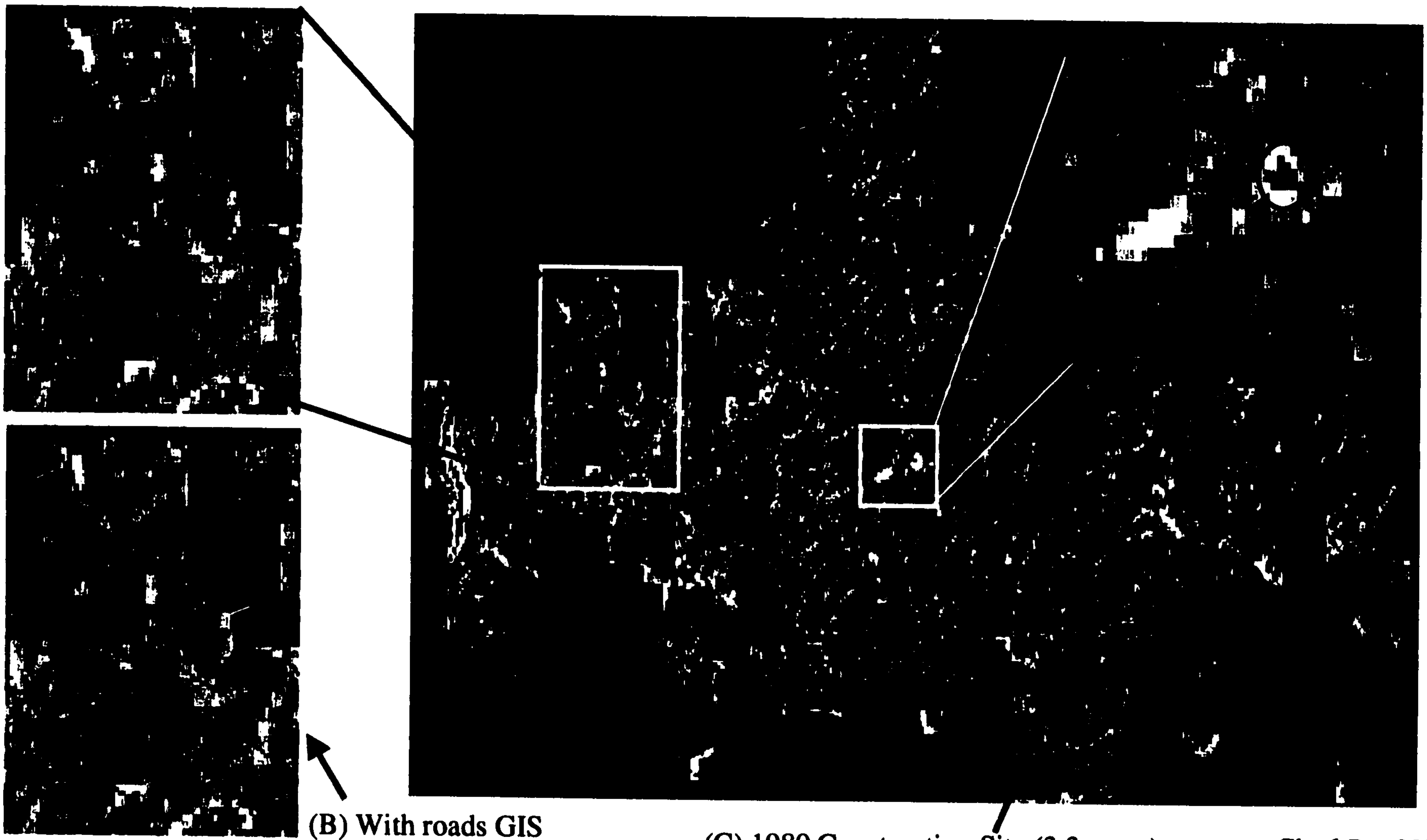


Figure 6-28:

% Xeric Vegetation, % Soil and % Mesic Vegetation of 1980 Construction Site
(Hypothesized Trajectory Soil: 72-lower, 85-higher, 92-higher)
(Hypothesized Trajectory Xeric Vegetation and Mesic Vegetation/Shade: unknown)

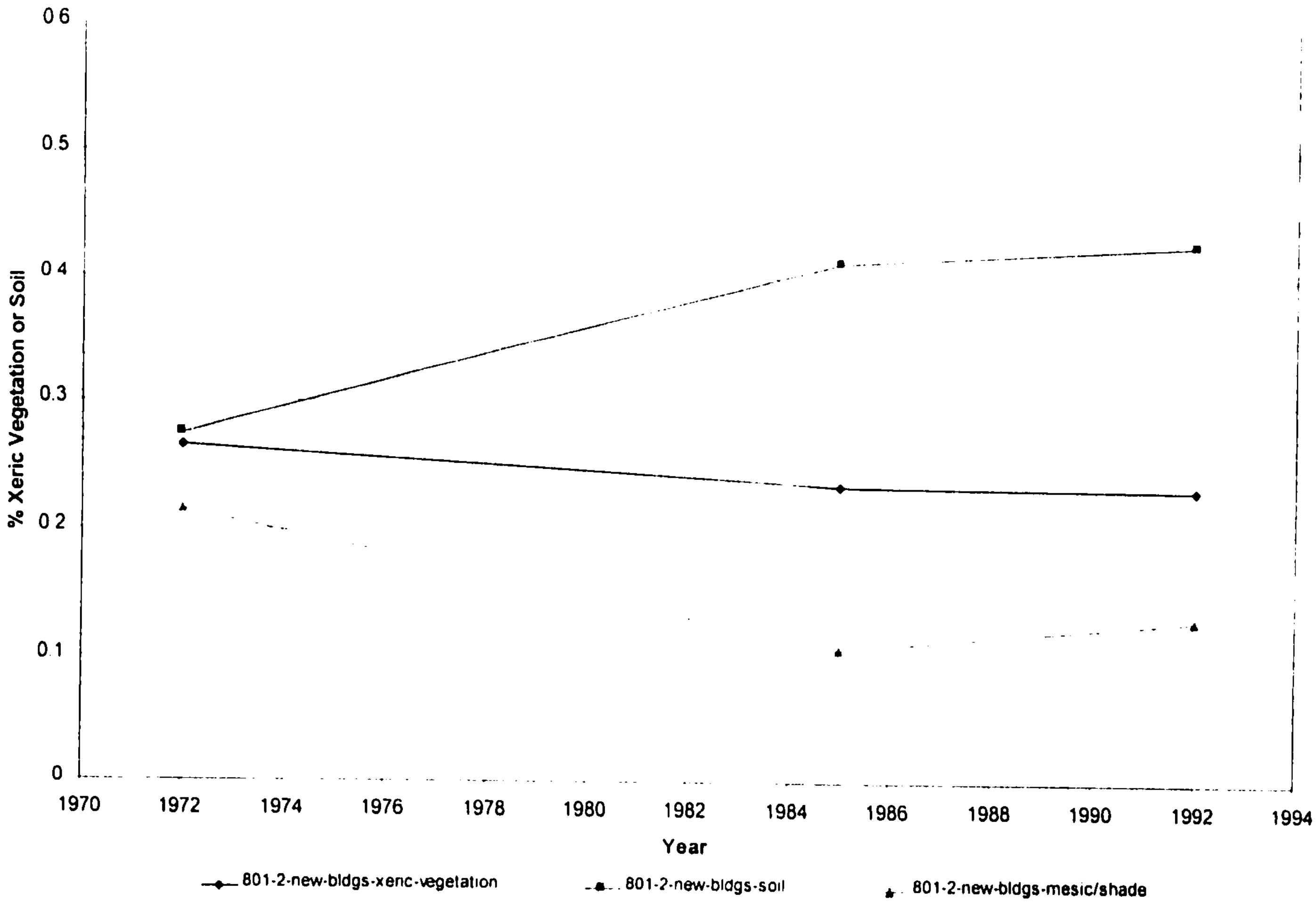


Figure 6-29: Timeline of Various Cutting Occurrences in the Northern Portion of the Morgan-Monroe State Forest
(The year of the cut and a letter provides a name for each cut)

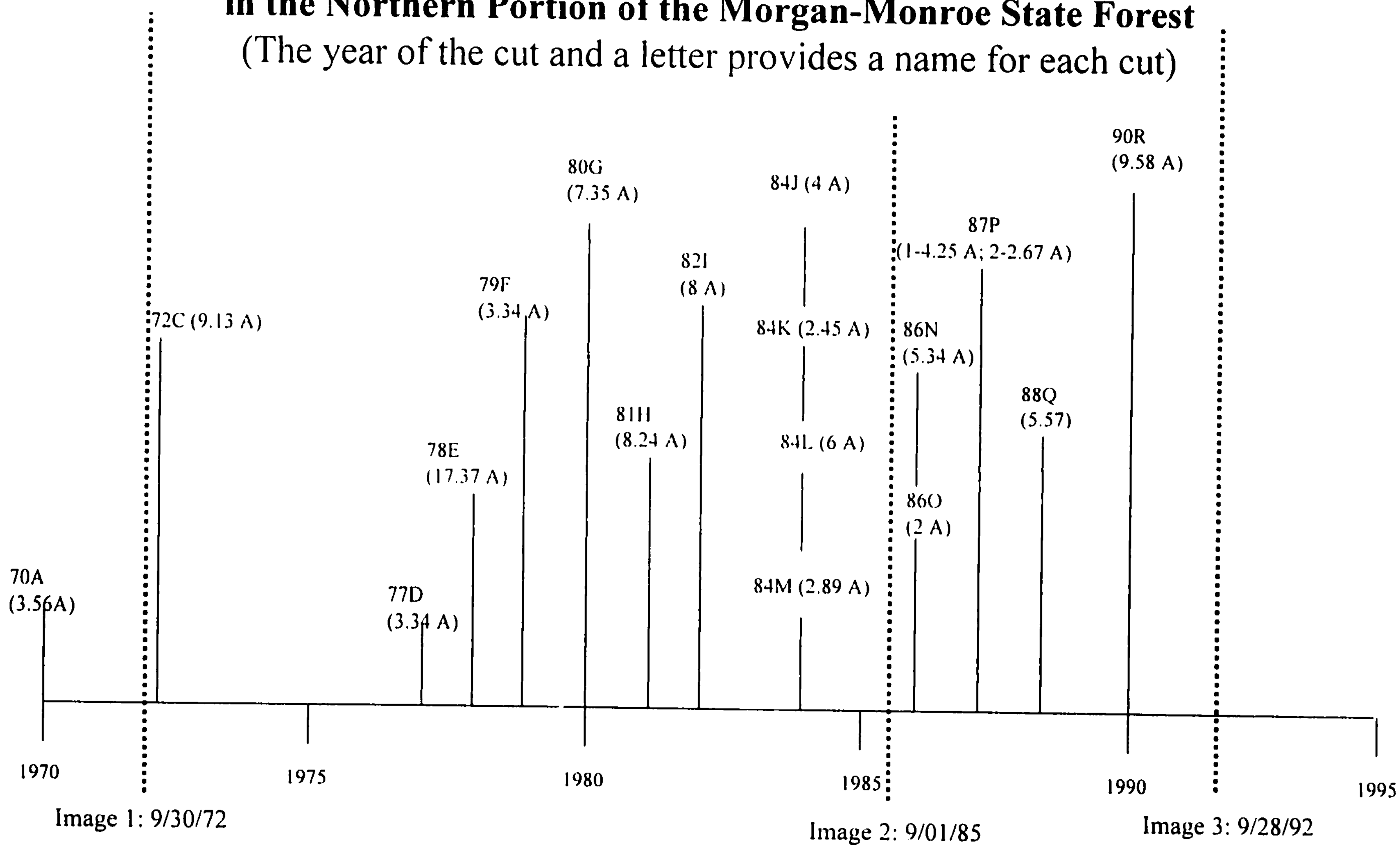


Figure 6-30:

Areas Cut Between 1985 and 1992 That Follow Hypothesized Trajectory (Hypothesis: 72-low, 85-lower, 92-high)

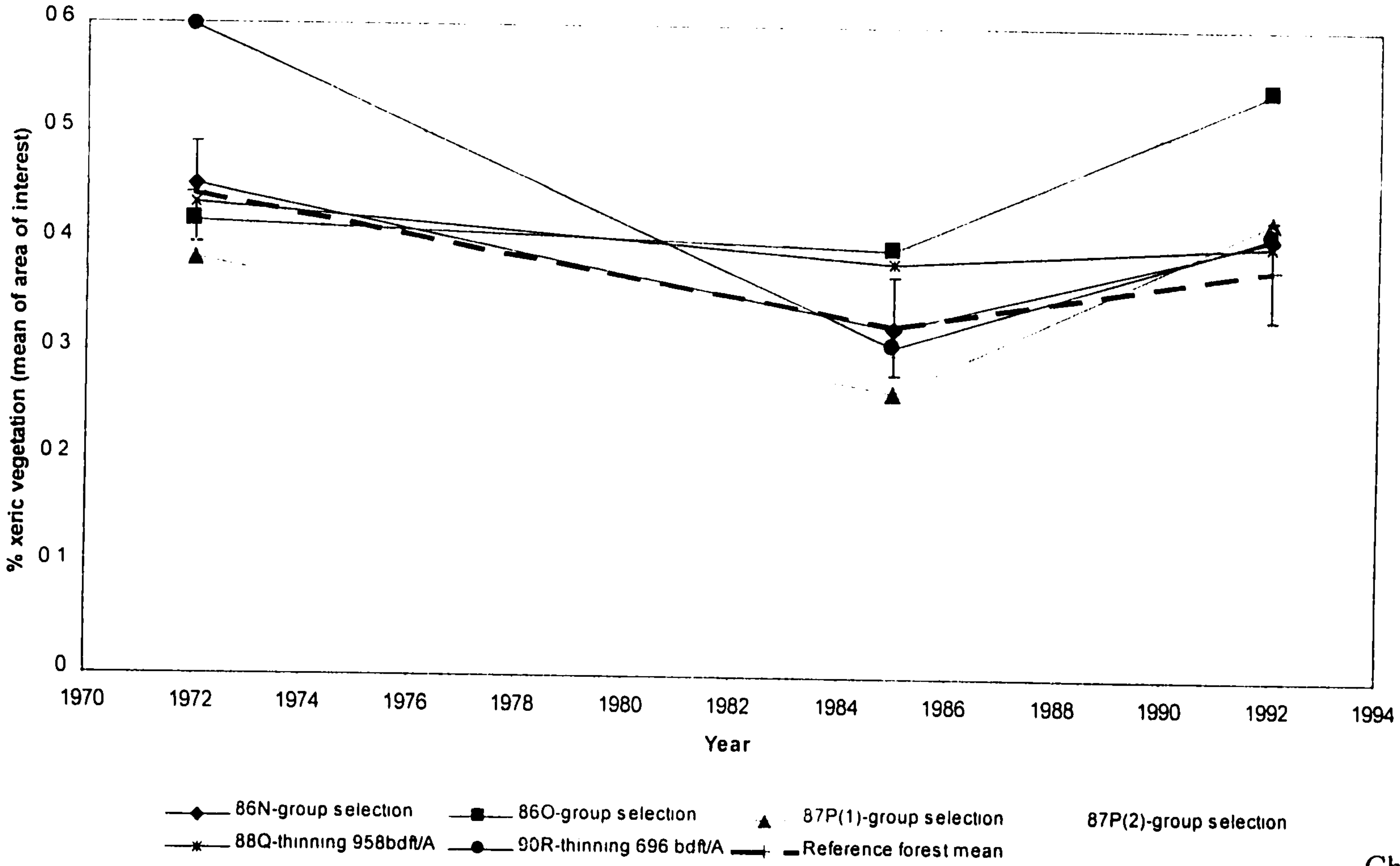


Figure 6-31:

Areas Cut Between 1985 and 1992 Do Not Follow Hypothesized Trajectory
(Hypothesis: 72-low, 85-lower, 92-high)

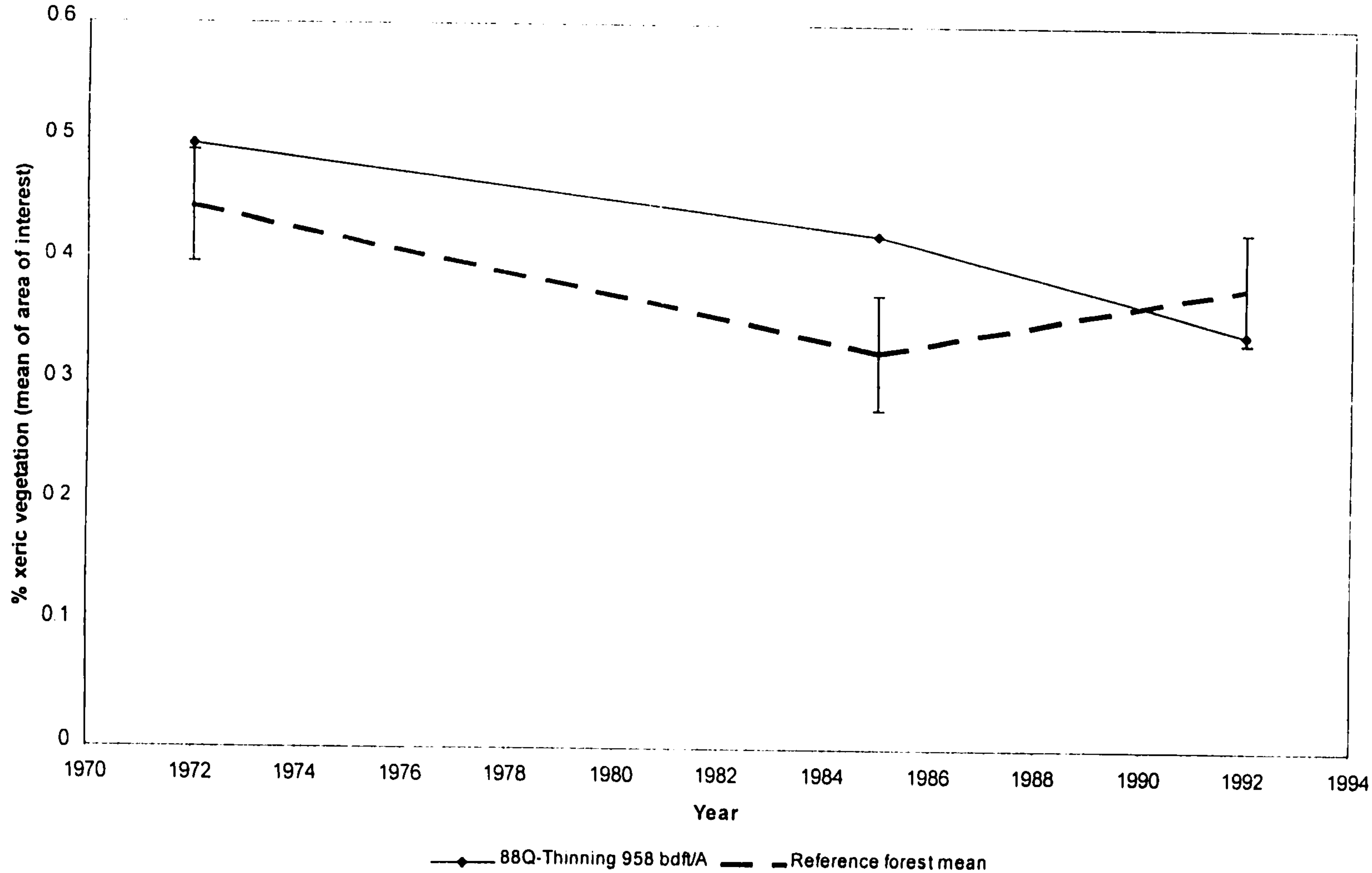


Figure 6-32:

Areas Cut Between 1972 and 1985 That Follow Hypothesized Trajectory
(Hypothesis: 72-low, 85-higher, 92-low)

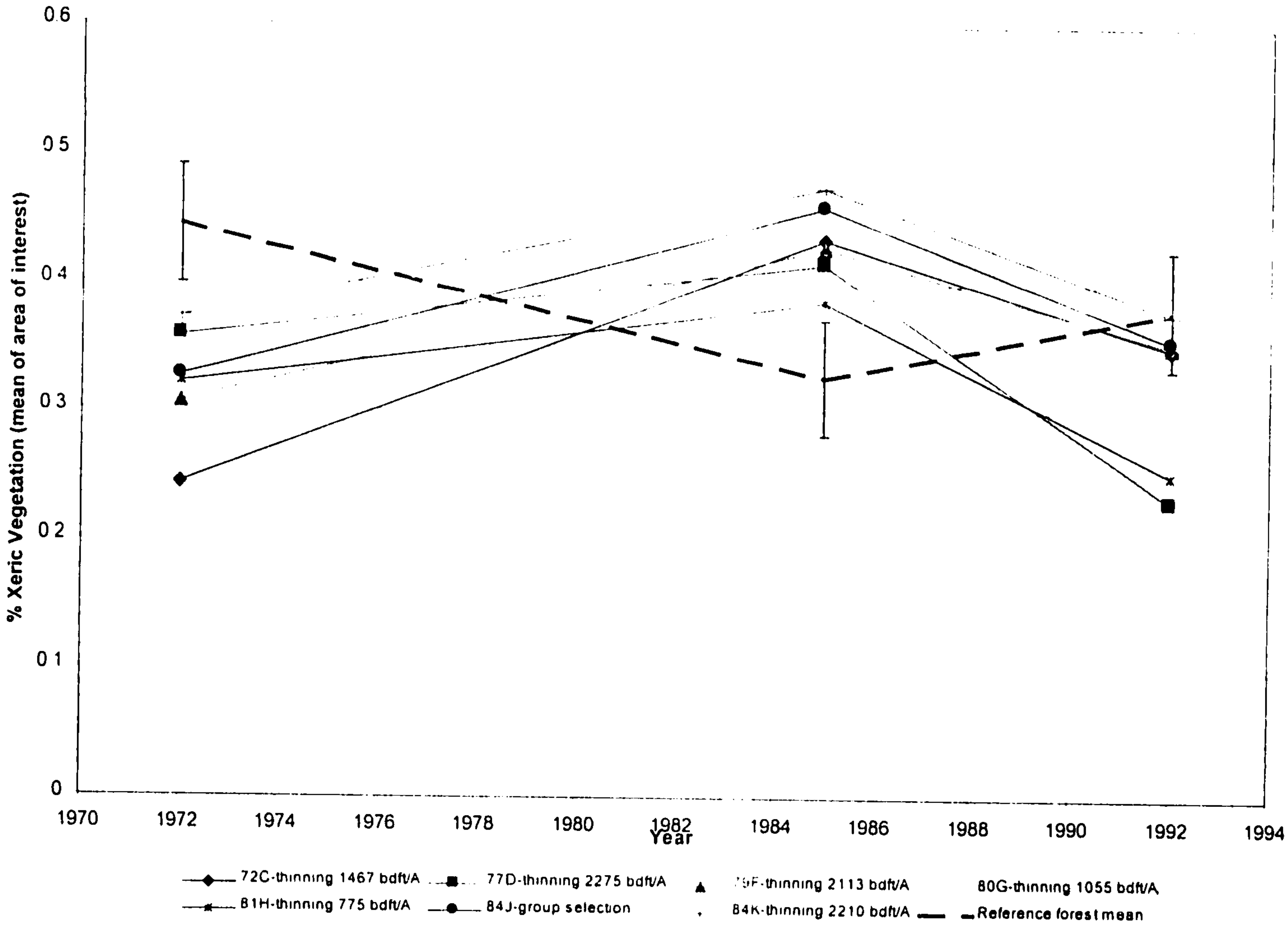


Figure 6-33:

Areas Cut Between 1972 and 1985 Do Not Follow Hypothesized Trajectory
(Hypothesis: 72-low, 85-higher, 92-low)

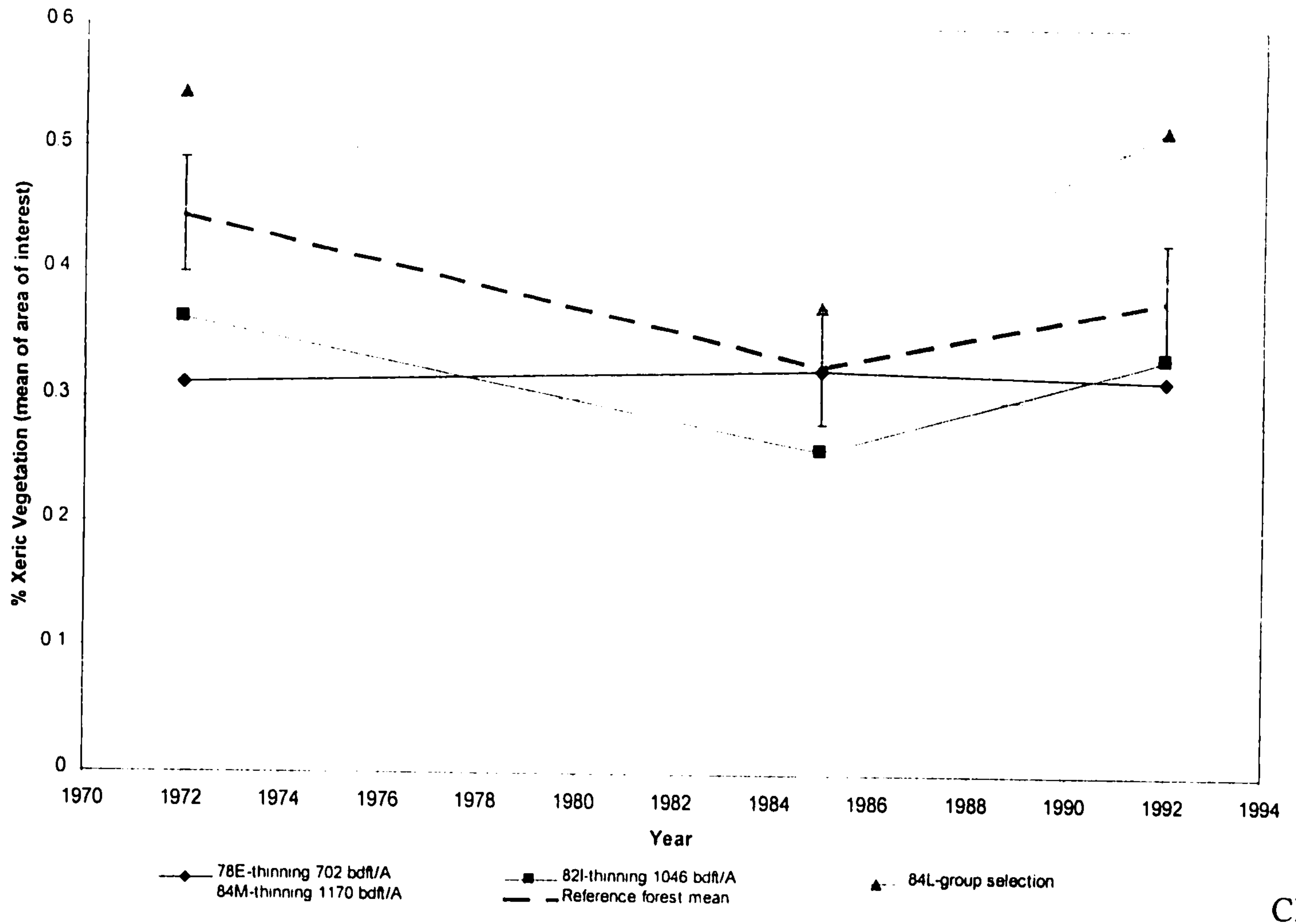


Figure 6-34:

Areas Cut Before 1972 That Follow Hypothesized Trajectory
(Hypothesis: 72-high, 85-lower, 92-lowest)

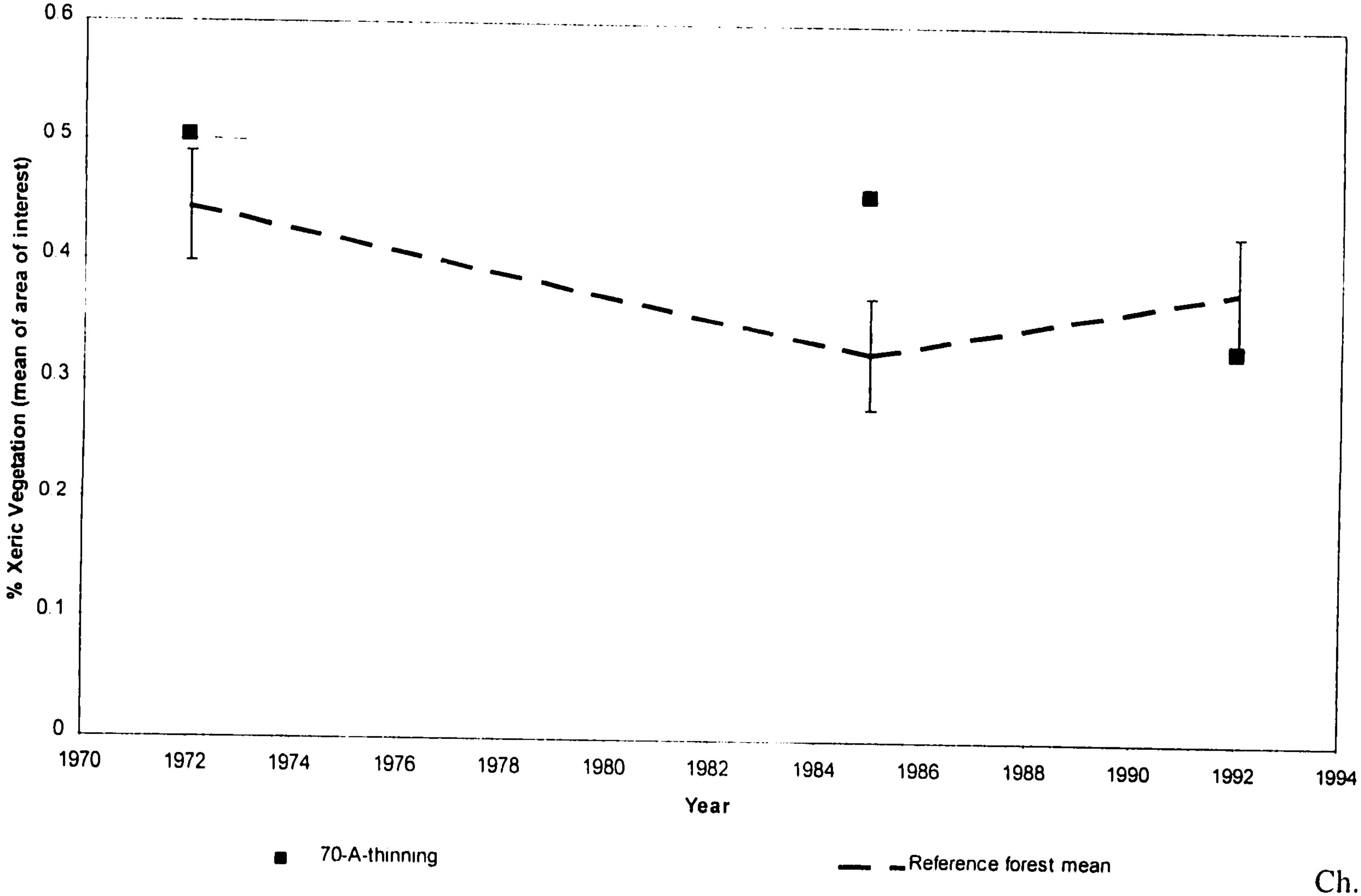
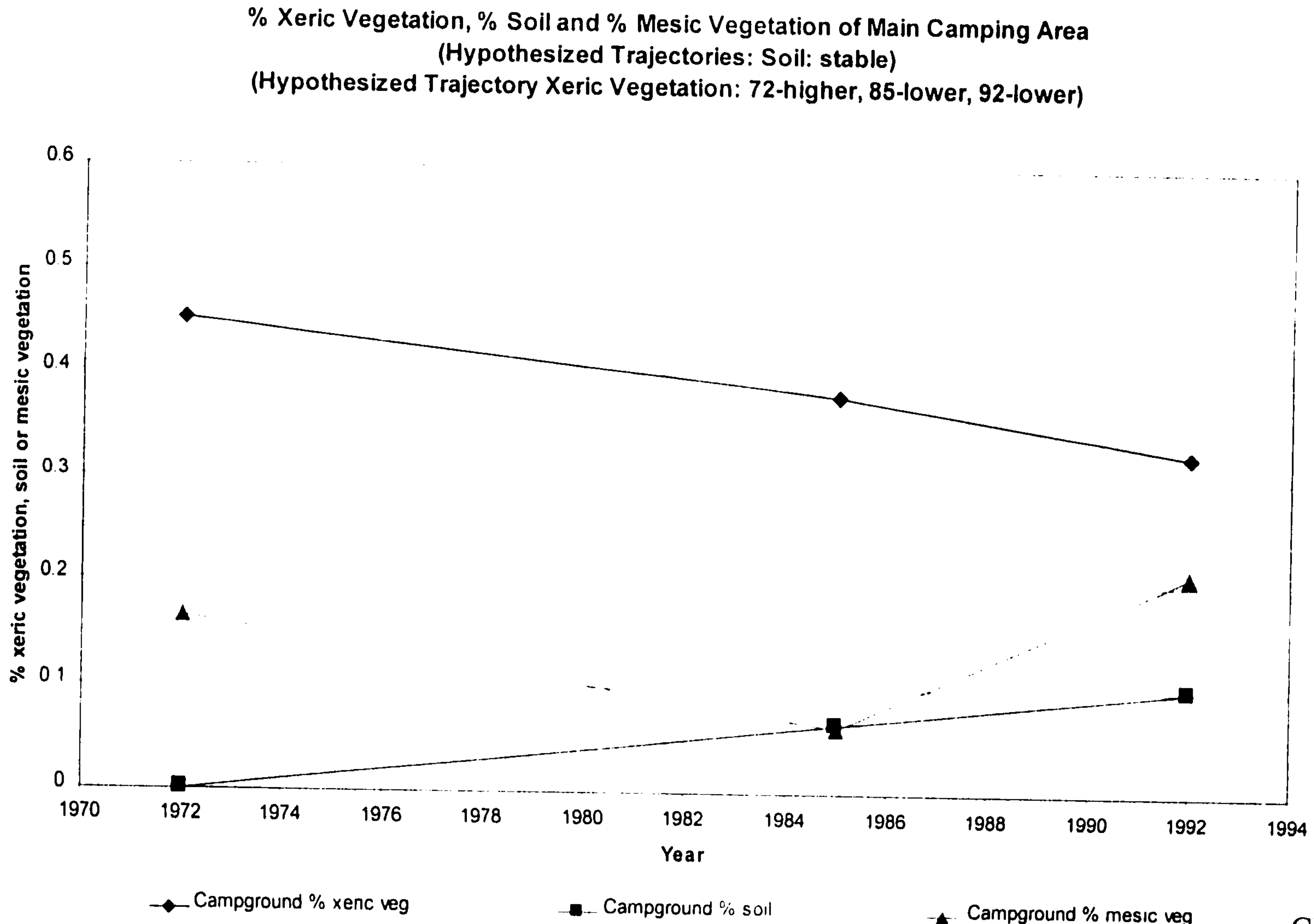


Figure 6-35:


% Xeric Vegetation, % Soil and % Mesic Vegetation of Main Camping Area
(Hypothesized Trajectories: Soil: stable)
(Hypothesized Trajectory Xeric Vegetation: 72-higher, 85-lower, 92-lower)
% xeric vegetation, soil or mesic vegetation
0.6
0.5
0.4
0.3
0.2
0.1
0
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
Year
Campground % xenc veg
Campground % soil
Campground % mesic veg

Chapter 7

LINKING INCENTIVES TO REMOTE SENSING OUTCOMES: TESTING STATE AND NATIONAL FOREST MANAGEMENT HYPOTHESES

Chapter 6 tested the sensitivity of a Landsat MSS image time series to human activities in a representative deciduous forest in south central Indiana. It provides empirical evidence of human activities and outcomes as measured by MSS spectral trajectories. Table 7-1 presents a summary of the findings from Chapter 6. Armed with this knowledge, we now are in the position to test the hypotheses established in Chapter 4.

This chapter is organized into three main sections. The first section tests the four hypotheses related to the property management of the Hoosier National Forest Pleasant Run Unit (HPRU 1 through HPRU 4). The second section tests the two hypotheses related to Yellowwood State Forest property management (YW 1 and YW 2) and the Hoosier-Yellowwood comparison hypothesis (HPRU-YW 1) presented near the end of Chapter 4.

Chapter 6 makes an important contribution to this study for it provides strong evidence that the results of human actions on deciduous forest landscapes can be identified using time series of MSS data. But, in at least one respect, the analysis of Chapter 6 was easy, I knew *a priori* where geographically and when temporally human actions had occurred. The analysis I undertake in this chapter is more difficult, for it is here that I now try to "scale up" and test hypotheses about human incentives, actions and outcomes over time across a particular physical and institutional landscape. We know from Chapter 6 that many of the human actions leave a spectral imprint, but whether these actions make a significant enough impact on the broader landscape such that they are identifiable without secondary information (e.g., toposheets with cutting areas delineated on it by the foresters themselves) is an open empirical question.

How do we move from an analysis of known activity locations as was done in Chapter 6 using "spectral trajectory graphs" to the study of broader physical and institutional landscapes? How would we, for example, examine change across the whole Hoosier Deam Wilderness area? One relatively simple approach would be to develop change "color composite" maps using the image data themselves or using one of the endmembers for multiple years. Recall Chapter 6, Figure 6-24, where a change map of the xeric endmember helped to identify areas around a road that was at one time widened and then thereafter continually maintained. This map was created by assigning the percentages of the xeric endmember for one time image to the red "color gun," another time point's percentage xeric data to the green color gun and the third time point's percentage xeric data to the blue color gun. Because these data are continuous, they combine to create many different colors with many different shades. Over a full landscape, this becomes overwhelming: there are too many colors and shades to easily interpret it. Interpretation was possible in Chapter 6 because I knew where to look—I had the cutting maps drawn by the property resource managers. It is much harder to pick up change in a sea of colors, representing subtly different change histories, when no secondary documentation exists.

A Classification Approach Based on Spectral Mixture Analysis Fraction Images

Classification is one primary method humans use to help deal with this problem of information overload.[1] However, as I described in Chapter 5, traditional classification maps generated from multispectral images have two primary limitations. First, traditional image classification techniques assign only one land category to each pixel. In reality, a 79 x 56 meter MSS pixel—about the size of a U S football field—will usually comprise more than one land cover form. Simple one category per pixel classifications are found to be too coarse for some analytic situations. Second, "raw" or partially processed images are often used that rely on satellite digital numbers representing reflectance in space rather than fully processed images representing at-surface reflectance (Green, Schweik and Hanson, 1998). Classifications based on the former have other variation in them (e.g., atmospheric and sensor effects) and therefore are image specific and cannot be applied to other locations. But what the global environmental change research community needs to be working toward is the development of satellite image based classifications that can be replicated in comparable locations (e.g., similar forest types) by other researchers.

The images used in this study have been processed to at-surface reflectance and therefore can be used to overcome these limitations in traditional classification processing. By applying spectral mixture analysis (SMA) to these images, the at-surface reflectance image data were converted to percentages of "pure" spectra or endmembers. By reporting the selected endmembers utilized in Chapter 6, Figure 6-13 and Table 6-1, I have initiated the development of a "spectral library" of pure land cover features for the south-central Indiana landscape. This process produced four "gray scale" images for each time point: (1) soil; (2) xeric vegetation; (3) mesic vegetation and other components (shadow, pine); and (4) RMS error. The pixels contained within each of the first three endmember images have numeric values representing percentages of land cover falling within that category. Importantly, these data represent mixtures that are based on the physical property of at-surface reflectance.

These SMA images can be applied to create land cover classes that move beyond the traditional one-category per pixel technique. For any time point, each endmember, theoretically, should represent a percentage between zero and one and the values of a pixel for all three endmembers combined should add up to one (100 percent). The challenge of the procedure is to find pure land cover spectra that can be used to explain the variation in all three time point images. The four band MSS images place an additional burden in that only three endmembers can be used. While there are some pixels where the three endmember fractions do come close to adding up to one, most have some RMS error associated with it. Given the error involved, it is reasonable to consider a pixel containing 40 percent or more of one type of endmember to be dominated by that endmember. Ranges supplied in Table 7-1 also assist in creating these class definitions.

I therefore define the first class—xeric forest—as having 40 percent or more in the xeric endmember (Table 7-2). A pixel falling under the second class—soil—is defined similarly and contains 40 percent or more of the soil endmember. Recall that the use of MSS images limits SMA to only three endmembers. Consequently, the darker mesic endmember spectra (see Figure 6-13) captures both the influence of mesic vegetation but also other dark reflectance such as pine and shadowed areas not successfully removed using topographic normalization procedures. A pixel consisting of 40 percent or more of the mesic endmember may be mesic forest, but it also might be a pine stand or an area exhibiting a high percentage of shadow. Finally, a mixed class representing a combination of xeric and mesic vegetation (each $\geq$ 20 percent) is included for often stands will have both properties.[2] This classification scheme is important for it: (1) is based on at-surface reflectance and documented endmember spectra (Figure 6-13) that researchers can apply to other locations with similar forested landscapes (e.g., other midwestern U.S. deciduous forests); and (2) moves beyond the "one category per pixel" classification scheme toward mixed classes by including the fourth xeric/mesic category.[3]

Based on this scheme, I developed an ERDAS Imagine™ model to convert the SMA percentages of each pixel to a new classified image based on the criteria summarized in Table 7-2. Classification maps were created for both Hoosier National Forest and Yellowwood State Forest for each of the three MSS time points. GIS layers representing the institutional landscapes (Chapter 4, Figures 4-5, 4-6 and 4-7) for each forest were then used to clip out areas falling under various institutional configurations associated with the hypotheses to be tested. The classifications for each area of interest for the two extreme time points (9/30/72 and 9/28/92) will be used in subsequent analyses. I developed classification maps for the 1985 image as well, but for most of the hypothesis testing only the two extremes are needed.[4]

Once the classified images are created for each time point, it is a straightforward task to generate change maps based on these classifications (see Figure 7-4 for an example). GIS functionality allows two (or more) time point classifications to be combined to create one map representing the change trajectory from one time point to another, then to another, etc. Of course, land cover change is bidirectional. For example, forests are converted to developed soil exposed areas, but soil areas also return back to forested areas (Schreier and Brown, 1992; Schweik, Adhikari and Pandit, 1997). Change maps and analyses of change need to be cognizant of the bidirectional nature of land cover conversions. Consequently, for each hypothesis, the following products of the area of interest will be generated: side by side MSS color composites; side by side temporal classification maps; a 1972-1992 change map; and a "forest dynamics" summary to assist the reader in interpreting the change map and to help understand the bidirectional nature of change.

Testing Hypotheses Related to the Hoosier Pleasant Run Unit

Four hypotheses related to the HPRU were presented in Chapter 4. Analysis for each one of these hypotheses will be addressed sequentially.

> *HPRU Hypothesis 1: Vegetation in the protected area of Deam Wilderness (area 5.1 in Figures 4-5, 4-6 and 4-7) will begin to show patterns of natural regeneration and little or no evidence of human activity.*

Recall from Chapter 4's discussion that the Deam Wilderness area of the Hoosier Pleasant Run Unit was dedicated in 1982. Well enforced and monitored operational-level rules in this area restrict commodity and development activities and encourage preservation and wilderness recreation activities (Table 4-6). To the property manager, the benefits of maintaining a wilderness area outweigh the costs of maintaining it. The costs of undertaking an activity not permitted in this area—measured in terms of citizen outcry, poor job performance evaluations, etc.—far outweigh the benefits of undertaking such an activity. We would expect then, that this area will likely exhibit the same spectral trajectories as was identified in the protected forested areas of the neighboring Morgan-Monroe State Forest in Chapter 6. There, vegetation moved from a relatively high percentage of the xeric endmember (40 percent or above) to a lower xeric percentage in

1992 (Table 7-1)

Figure 7-1 provides a simple, but useful, method to compare change at a landscape level It displays, side by side, the 9/30/72 MSS and the 9/28/92 MSS images in band 4 red, band 2 green and band 1 blue (R4, G2, B1) color composites Recall that in these types of composites, soil exposed areas take on a dark greenish look and vegetation appears more reddish The northeastern end of Lake Monroe is in blue-green at the top left side of the image Circled on this figure are seven major areas in Deam that in 1972 appear to exhibit some soil exposure which in 1992 appear to be almost entirely overtaken by vegetation In these areas, there has been a significant vegetation regrowth.

Figure 7-2 presents two endmember fraction-based classification maps generated for this same area of Hoosier On the left side of the figure is the map representing 9/30/72. On the right side is the map for 9/28/92. A side-by-side comparison of these maps reveals three easily detected changes

First, the northern peninsula of the Deam circled and labeled "A" in both maps shows a significant amount of exposed soil (gold) in the 1972 map, whereas in the 1992 map it is replaced by a combination of mesic vegetation/pine/shadow class (dark green) and the mesic/xeric vegetation mixture class (light green). A review of a later September 1997 TM image with better spatial and spectral resolution reveals a significant pine stand on this peninsula. Because pine is not indigenous to this area, this suggests that a major planting activity occurred in this area between 1972 and 1992. Given the location of this area–directly at one end of Lake Monroe–this conclusion makes logical sense. It appears that efforts have been made to protect soil erosion and the planting of pine suggests that the condition of the soil must have been particularly poor.[5] There is, then, some evidence of planting activity in this region–an activity not permitted in the rules related to the Wilderness–but given the size of the canopies in 1992 this activity probably occurred well before wilderness designation.

Second, the conversion of soil to vegetation as shown in Figure 7-1 is also apparent in the area identified by "B" in Figure 7-2. Scattered soil dominated areas (gold) in 1972 have been replaced by more prevalent xeric spectra (red), mesic/other spectra (dark green) or a mixture of the two (bright green). This also supports the contention that natural regeneration is occurring. Whatever the human activity being conducted prior to 1982's wilderness designation appears to have ceased or slowed down and the forest continues to grow back.

Third, the large circles on the maps in Figure 7-2 labeled "C" reveal a large area exhibiting what appears to be naturally produced phenomenon. Many of the stands that were xeric in 1972 remain xeric (red) in 1992. Figure 7-3 overlays just the xeric and mesic/xeric dominated pixels on a map of the digital elevation model for the region. The elevation data is shown in shades of gray where dark means lower elevation and bright means higher elevation. This comparison reveals that much of the xeric vegetation in 1972 that remains xeric in 1992 (red) resides in higher elevations—summits—which is what would be expected. But many other 1972 xeric vegetation dominated areas have been replaced by higher percentages of mesic vegetation (bright green or dark green areas) in 1992. These areas take on the expected high xeric to lower xeric trajectory that was found in the Morgan-Monroe analysis of the protected forest areas there (Figure 6-26; also Table 7-1). Moreover, the locations of the xeric to mesic/xeric conversions tend to, overall, make logical sense. They usually fall in geographic areas between mesic categories and xeric categories, exactly where we would expect these combinations to exist.

Figure 7-4 provides a third, more quantitative way to analyze landscape change that helps to articulate its bidirectional nature. It presents a "1972-1992 change map" overlaid on a "natural color" composite of the 1997 Landsat TM scene (R3, G2, B1). This map was produced using the model maker function in ERDAS Imagine™ and describes the dynamics in the Deam Wilderness region over the 1972-1992 period. But even when we move from continuous data to a classification map, the combination of two time points produces seventeen change trajectory classes (see the legend in Figure 7-4). This many categories are still very difficult to interpret visually. Consequently, Figure 7-5 is provided to help the reader understand the dynamics shown in the change map. In each of the two classification maps, there are four main land cover categories: soil, xeric vegetation, mesic/xeric and mesic/other shown in boxes in Figure 7-5. Arrows between them describe the direction of change from 1972 to 1992. Adjacent to each arrow is the number of pixels and percentage of total pixels that converted from one category in 1972 to another (or the same) category in 1992.

This figure shows the multidirectional nature of land cover change. Each of the four categories exhibits some change to the others over time. However, Figure 7-5 makes it apparent that the most significant change in the Deam is a shift from xeric and mesic/xeric vegetation to the mesic/other category. Notice that the mesic/other category exhibits a 9 percent gain in land area over the 1972-1992 period. It is important to remember that because of the four band limitation in MSS images, this mesic/other category includes the influence of shadow, pine and other land cover that did not fit well (e.g., clouds). However, because both images are taken at the same time of day, topographic shadow not removed by topographic normalization should be the same in both images The only shadow that would change would be that caused by cutting or some other forest disturbance activity A careful search of the MSS images for this region specifically looking for shadowed clear cut areas revealed none in the 1992 image. One percent of the increase to the mesic/other category is from area that in 1972 was soil that has now converted partially to pine. This is the circled area labeled "A" in Figure 7-2. Another two percent increase in mesic/other is attributed to 1972 cloud cover (Figure 7-2 D. see also the bright cloud in the 1972 MSS image in Figure 7-1). The other 6 percent increase in mesic/other is attributed to the maturing of xeric and xeric/mesic vegetation moving toward an older, more mesic spectra

This last point requires a more thorough explanation If we pause to reflect on the discussion of the Hoosier National Forest history, we realize that most of the land it encompasses was, at one point, former agriculture land. In the 1930s the adjacent Lake Monroe was nonexistent[6] Much of the Deam Wilderness area was at that time under cultivation or recently abandoned. Aside from the pine stands that were planted by the CCC during the 1930s and 1940s, we can assume that many of the forest stands visible in the 1972 MSS image probably were early successional forests in the 1930s or 40s. This means that much of the forest vegetation, by 1972, were probably 30 to 40 years in age and exhibited a higher percentage of xeric spectral qualities. By 1992, they exhibit a lower xeric endmember percentage and more mesic characteristics because they have aged 20 years.[7] Their root systems provide access to more water and more of the leaves in the canopy are hidden from direct sunlight. Some stands with adequate water availability may be exhibiting a gradual replacement of more xeric vegetation such as oak-hickory with more mesic, mixed deciduous hardwoods such as beech and maple.[x]

This analysis provides strong support of hypothesis HPRU 1. Vegetation in Deam is taking on the same regeneration trajectory as was revealed in the protected areas of Morgan-Monroe (Figure 6-26). There also was the discovery of unexpected human induced preservation activities (pine planting) that appear to have been undertaken prior to the establishment of the wilderness area rules.

> *HPRU Hypothesis 2: Areas designated as 3.2 (multiple use) prior to 1985 (refer to Figure 4-5) that later were designated as 6.1 or 8.3 in 1985 (refer back to Figure 4-6) and 6.2 in 1991 are expected to show patterns of natural regeneration.*

Figure 7-6 provides MSS (R4, G3, B2) color composites for the area within the Hoosier Pleasant Run Unit that had a 3.2 rule designation prior to 1985, had a 6.1 rule designation between 1985 and 1991 and has a 6.2 rule designation from 1991 onward (refer to Chapter 4, Tables 4-4 through 4-6 for specifics). The boundary in this figure is a general one from the 1985 Plan, and doesn't designate the private property areas that exist within the region. Cutting had been permitted in this area until the 1991 Plan Amendment, but it appears that because of its proximity to the Deam Wilderness and Lake Monroe, more emphasis in the 1980s and 1990s has been given to provide "mature hardwood" (USDA Forest Service, 1991) wildlife habitat and preservation activities. This suggests that, like Deam Wilderness, this area too should exhibit a higher degree of natural regeneration patterns. The cost/benefit calculations of forest property managers who follow well-designed rules that are closely monitored by external citizens are expected to place a higher value on non-harvesting activities in this region. Consequently, areas that are not topographically constrained in terms of water availability are expected to exhibit higher xeric endmember percentages in 1972 and lower xeric percentages in 1992 like what was discovered in the protected areas of Morgan-Monroe (Table 7-1).

The classification maps based on endmembers are provided in Figure 7-7 and exhibit the general 1985 6.1 boundary as outlined in the Plan's published maps. This provides an excellent example of how the Hoosier National Forest (and Yellowwood State Forest) landscape contain scattered parcels of private property within their general boundaries. The 1992 Hoosier National Forest GIS coverage[9] allows us to distinguish between Forest Service-owned land and the private land that cannot be identified using the 1985 Plan maps alone. The colored areas aside from gray are Forest Service property within the Pleasant Run Unit that follows the "3.8 to 6.1 to 6.2" institutional history.

Interpretations of the two classification maps in Figure 7-7 follow the same logic as the previous analysis of the Deam Wilderness area. Note that in the 9/30/72 color composite image in Figure 7-6 several clouds (bright white) and their shadows (dark) are apparent. These areas are classified in the "mesic/other" category (dark green) (Figure 7-7 A). Care must be given not to misinterpret change due to these clouds in the 1972 image.

This area exhibits two apparent signs of forest regeneration. The first sign, perhaps less striking than the second but important nevertheless, falls in the southern part of the region, designated "B" in Figure 7-7. In 1972 there existed a relatively small area exhibiting exposed soil that in 1992 displays more mesic/xeric vegetation qualities. Visual confirmation on a 1997 Landsat TM scene with better spectral and spatial resolution confirms this conclusion. It is not clear, however, whether this pattern is naturally produced or is a result of some sort of human-induced planting activity. The second sign of regeneration in this area is broader in scope. A visual inspection of the two classification maps in the circled area of Figure 7-7 C gives the appearance of natural regeneration as vegetation moves from a more xeric (red) spectral quality in 1972 to more of a mesic/xeric (bright green and dark green) spectral composition in 1992.

The change map and more quantitative forest dynamics summary (Figures 7-8 and 7-9) for this area confirm these conclusions. What little exposed soil existing in 1972 has by 1992 converted to either mesic/xeric vegetation or mesic/other categories. Only eighteen soil dominated MSS pixels exist in 1992 out of a total of 23,895 pixels that comprise the area.[10] Both xeric vegetation and mesic/xeric mixtures exhibit a 4 percent net loss of their 1972 land cover and much of this has converted to the mesic/other category. Although some of this is attributed to the cloud cover in the area, the region identified by circle "C" in Figure 7-7 has few clouds and still reveals this conversion. I estimate that at least 5 percent of the xeric and xeric/mesic conversion to mesic vegetation can be attributed to the gradual conversion of vegetation toward a more mesic leaf morphology over time. This is comparable to what was found in the Deam Wilderness area above.

Finally, a visual review of the 1997 TM image looking for evidence of cutting or other human produced disturbance revealed no evidence of these activities. In short, this analysis confirms the HPRU 2 hypothesis.

> *HPRU Hypothesis 3: Areas managed for intensive recreation (e.g., 7.1 in Figures 4-6 and 4-7) are expected to reveal a higher level of stable exposed soil, perhaps some new forest to soil conversion for new facility development, and natural regeneration in the form of mature canopy protected for visual enhancement.*

Figure 7-10 provides color composite images for the Pleasant Run Unit's intensive recreation area which is adjacent to Lake Monroe. This area has been designated "intensive recreation" for all three Hoosier Pleasant Run institutional time periods (Figures 4-5, 4-6 and 4-7). Figure 7-11 provides the endmember-based classification maps of this area for the two extreme time points. Note the prevalence of exposed soil in the 1972 classification map (identified by circles labeled "A"). Recall that the Morgan Monroe study of one camping recreation area in Chapter 6 revealed a lower percentage of exposed soil in 1972 and a larger percentage of exposed soil in 1992. I expect to find this area exhibiting either stable or increasing soil exposure over time.

Note in the 1972 map in Figure 7-11 that there is more soil endmember dominated pixels than found in other previously studied areas. This isn't surprising, because it is one of the more extensive recreation areas in the region. The soil exposure in 1972 captures the recent development activities that were undertaken to supply recreation-based facilities adjacent to Lake Monroe reservoir which had been created only seven years previously. Note, however, that in the 1992 classification, much of the exposed soil has returned to areas dominated by mesic and mesic/xeric vegetation. This differs from what was identified in the Morgan-Monroe study and the expected trajectory. Much of this change can be attributed to the mature trees the property managers try to encourage for visual enhancement around recreation facilities. As the trees have aged, their canopies have grown and now appear to cover many of the developed areas (for example, the road network by the boat launch or picnic areas) more fully.

Besides the more prevalent soil areas, other parts of this region exhibit the same signs of natural regeneration that we have seen earlier. The circle labeled "B" in Figure 7-

11 encompasses another forested area following a similar natural regrowth spectral trajectory as vegetation moves away from the xeric toward a more mesic quality This is confirmed in the analysis of the change map and the corresponding forest dynamics summary supplied in Figures 7-12 and 7-13 The number of pixels dominated by the mesic/other endmember has increased by 12 percent between 1972 and 1992 largely from forest conversion from xeric and mesic/xeric vegetation. The extent of this shift is actually higher than what was found in the Deam Wilderness area and may be attributed to water availability changes resulting from the creation of the reservoir

The findings support hypothesis HPRU 3 This area exhibits natural regeneration as a result of the emphasis on visual enhancement Relative to the other areas, this area also has had a higher degree of soil exposed, shown especially well in the 1972 classification map (Figure 7-11). What is surprising is that, over time, the percent soil exposed throughout much of the management unit has converted to more of a vegetation spectral quality One explanation is that the existing trees around development have increased their canopy size, thus covering more of the developed areas (such as roads, picnic areas). The reflectance received by the satellite sensor is more of the leaf area of larger, more mature trees

> *HPRU Hypothesis 4: Areas that have been designated as "multiple use" over time (e.g., 2.8 in Figure 4-7 that prior were designated 3.1 or 3.2) are expected to reveal mixed spectral trajectories, exhibiting some limited patterns of cutting and access road construction. Given the intense pressure the Forest Service has received from the public in the mid-1980s and 1990s over cutting initiatives, it is expected that spectral patterns of cutting in these areas will exist, but in limited areas.*

Some of the more southern and eastern areas of the Hoosier Pleasant Run Unit have had consistent institutional configurations that permit timber cutting. Recall from Chapter 4 that clearcutting was the Forest Service silviculture method of choice during the 1970s and 1980s The analysis of cutting trajectories of the Morgan-Monroe forest revealed that MSS time series data is in fact sensitive to groups selection cutting. Clearcuts typically affect a larger geographic area and should also be apparent on the images The analysis of the Morgan-Monroe revealed that cut forest exhibits a higher percentage of the xeric endmember. In other words, younger forest vegetation provides a more xeric appearance. The dominance of the xeric endmember diminishes over time as the cut area continues to grow back

However, the examination of timber cutting in Morgan-Monroe revealed a more complex set of spectral trajectories that depends on when the cutting occurred and how much was removed (Table 7) In general, Chapter 6 discovered that three dominant trajectories appeared to exist Vegetation cut after 1985 exhibited a high (> 40%) xeric look in 1972 and in 1992 continued to exhibit a high (> 40%) xeric look. Earlier vegetation, cut between 1972 and 1985, had a medium (20-39%) xeric look in 1972 (most likely attributing the older stand age), and remained in the medium category in 1992. Vegetation cut prior to 1972 exhibited a high xeric (40-50%) spectra in 1972 and then a medium xeric quality in 1992. This reveals that, depending on the rotation period, the spectral trajectories are relatively complex and appear to relate directly with age class.

I hypothesize then, that areas falling under an institutional landscape permitting clearcut activities—such as the 2.8 designated region—will follow similar patterns. Maturing, more mesic looking stands perhaps forty to fifty years old (or older if the stand existed during the 1930s) in 1972 that were subjected to clearcutting during the 1970s or 1980s would be replaced with a medium or high xeric look in 1992. This new vegetation could be anywhere from one to nineteen years of age depending on when the clearcut was undertaken. Consequently, in general we would expect then a more stable xeric or mesic-xeric looking landscape than we have seen in other more natural regenerating regions (red color in the classification and the change maps). We also would expect a higher degree of the xeric and xeric-mesic endmember across this area as areas subjected to clearcutting in the earlier 1970s (e.g., 73-75) begin to move from a more xeric spectra toward a more mesic spectra. Finally, we would expect late 1980 and early 1990 clearcut areas to exhibit some exposed soil from skidder and logging trails.

One difficultly in this analysis is that the area is large and geographically dispersed compared to other areas studied. For analytic consistency, Figure 7-14 provides the side-by-side color composites, but these are presented at a much broader scale making interpretation difficult. Cloud cover over this region in the 1972 image is prevalent. Therefore, analysis here must also be careful not to attribute land cover change to these regions because the cloud cover artificially raises the "mesic/other" category in change dynamics analysis. Figure 7-15 displays the side-by-side endmember classification maps and Figure 7-16 provides the accompanying classification change map of the area overlaid on the September 1997 TM natural color composite. The legend is removed (see Figure 7-12) to make interpretation easier for the reader.

In general, based on soil and vegetation analyses, HPRU Hypothesis 4 is not supported. Little exposed soil exists in the 1992 classification. In fact, like other areas, the soil-dominated areas identified in the 1972 classification have largely disappeared in the

1992 classification with the exception of the major road in the area. One example of this is shown in the enlarged area designated by Figure 7-15 B, where a geographically distinct parcel exhibits signs of conversion from soil (gold) back to xeric (red), xeric/mesic (light green) and mesic/other (dark green) vegetation. It is very likely that this is a newly purchased parcel that is now undergoing conversion from former agriculture land to a forest stand of 10-20 years of age.

There are a few locations that do exhibit a pattern that strongly suggests a cut was undertaken sometime between 1972 and 1992. Figure 7-17 provides an example. As expected, in 1972 the stand circled in Figure 7-17 A (classification map) and 7-17 B (the 1972 MSS R4, G2, B1 color composite image) exhibits a mixed mesic/xeric spectra. The stand very likely had at the time some valuable hardwoods and resided in an area that was fairly easily accessed (a road is nearby and it is relatively flat terrain). In 1992 (Figures 7-17 C and D), the same area exhibited a much more xeric appearance with high values in the infrared band suggesting that a younger stand exists in that location. The geographic consistency gives the appearance of a clearcut region that follows the high percentage xeric in 1972 to high percentage xeric in 1992 that is representative of a cut that occurred between 1985 and 1992 (Table 7-1).

While there are some examples such as this that exhibit some cutting spectral footprints, a more broad geographic scale review of the classification maps (Figure 7-15), the change map (Figure 7-16) and the forest dynamics summary (Figure 7-18) reveal a change pattern for this area quite similar to the more protected areas analyzed earlier (compare the forest dynamics of Figure 7-18 to Figures 7-13, 7-9 or 7-5). This area appears to be exhibiting a high degree of natural regeneration spectral trajectories moving largely from a more xeric look to a more mesic/xeric look. There is one area of exception, circled in white in the change map of Figure 7-16. A review of the 1997 Landsat TM scene shows that this area has a high representation of pine stands than other areas, and therefore reveals less xeric properties and more mesic/other (other being pine) as a whole. The forest dynamics summary in Figure 7-18 reveals that the "2.8" designated area, as a whole, exhibits the highest net increase in the mesic/other category of all the Hoosier areas analyzed. But this is an artifact produced by the significant cloud cover in the 1972 image for this area. Somewhat to my surprise, this area exhibits a similar change trajectory to the other more protected areas of the Pleasant Run Unit.

Hoosier HPRU Conclusion

This analysis supports three of the four HPRU hypotheses. There are two explanations why the fourth HPRU hypothesis is not supported and my sense is that they are both contributing factors. The first explanation relates the institutional environment of Hoosier during these decades. Given the constantly growing public pressure on the Forest Service regarding clearcutting activities anywhere in the forests from the late 1970s onward, the amount of actual timber production the Hoosier forest property manager may have decided to undertake may be minimal when compared to the size of the Pleasant Run Unit property as a whole. As articulated in Chapter 4, to the property managers, the cost (largely in terms of public outcry and human labor to meet documentation procedures mandated by legislation) may have outweighed the benefits of undertaking the cut. If this is a correct assessment of the situation—and, I believe it is—then looking for clearcut sites across even the 1991 Plan's 2.8 designated area in Pleasant Run is a little like looking for a needle in a haystack. On the whole, area 2.8 exhibits a natural regeneration spectra because most of its area is in fact regenerating.

There is, though, the second explanation for the reason Hypothesis HPRU 4 is not confirmed. Although the Morgan-Monroe analysis proved that the MSS images are sensitive to human cutting activities, analysis at a landscape level, with no supporting documentation on where cuts occur, raises additional analytic problems. It could be that the analysis conducted here failed to identify more of the cutting locations. This second explanation will be explored in more depth in the discussion that follows the Yellowwood and comparative hypotheses testing

Testing Hypotheses Related to Yellowwood State Forest and Comparing Yellowwood to Hoosier

Two hypotheses related to Yellowwood and one hypothesis comparing Yellowwood to Hoosier were presented in Chapter 4

> *YW Hypothesis 1: High intensity recreation tracts will exhibit mixtures of vegetation and soil reflectance. Vegetation canopies in these areas and areas surrounding Yellowwood Lake will have a natural regeneration spectral trajectory over 1972-1992 as they are left untouched for visual enhancement purposes.*
>
> *YW Hypothesis 2: Tracts that are relatively easily to access and are not (1) directly adjacent to Yellowwood lake, (2) used for intensive recreation (e.g., campgrounds), or (3) comprised of a high degree of pine stands, will exhibit signs of timber production activities over the 1972-1992 period.*

And,

> *HPRU-YW Hypothesis 1: Given what we know about the incentive structures guiding property manager decision-making between 1972 and 1992 it is expected that Yellowwood will exhibit a higher level of human disturbance activities, particularly in terms of timber cutting, than*

anywhere in the Hoosier Pleasant Run Unit.

Let me test each one in sequential order.

YW Hypothesis 1 suggests that intensive recreation (e.g., camping, picnicking) tracts will exhibit an increasing percentage of soil dominated pixels and a maturing vegetation canopy. That is, the vegetation that is more xeric in 1972 should become more mesic in 1992 (Table 7-1). YW Hypothesis 2 suggests the opposite: tracts that are more likely to be used for timber production purposes are expected to exhibit a higher number of pixels with spectral properties that follow the look of cutting trajectories (Table 7-1). More of the pixels in 1972 that are dominated by mesic or mesic/xeric vegetation are expected to be converted to a more xeric or mesic/xeric look in 1992. The HPRU-YW hypothesis suggests that Yellowwood should exhibit a higher proportion of cutting-like spectral trajectories and will be in 1992 more xeric overall when compared to Hoosier Pleasant Run Unit locations. In order to test these hypotheses, we must first extract Yellowwood tracts that satisfy the conditions specified in YW Hypotheses 1 and 2.

Let me first try to identify tracts that are potential timber production areas for YW Hypothesis 2. Figure 7-19 displays the Yellowwood tract boundaries overlaid on the September 1997 Landsat TM Scene (natural color composite R3, G2, B1). The tracts outlined in white do not satisfy the conditions specified by this second hypothesis. These are tracts immediately adjacent to the lake or are used for intensive recreation (incidentally, many of the tracts around the lake meet both of these conditions). White outlined tracts that do not immediately surround Yellowwood Lake exhibit a high degree of pine stand within their borders. These were easily identified visually by displaying an available 9/26/97 TM image of the region in an all-infrared color composite (R4, G5, B7) where pine looks especially dark.

Figure 7-20 displays the 1972 and 1992 MSS images and the tract boundaries satisfying YW Hypothesis 1.[11] They delineate the high intensity recreation areas at Yellowwood and tracts enclosing Yellowwood lake that are likely to be maintained for visual enhancement purposes. Figure 7-21 displays the 1972 and 1992 classification maps for these tracts. A comparison of these two maps revealed three locations where soil is the dominant land cover. Field verification confirmed a camping and picnic area in 7-21 A. Areas circled by 7-21 B are soil-exposed areas adjacent and near the Yellowwood Lake dam. State records (IDNR, 1980) indicate building initiatives related to the property manager residence around 1980 that could explain part of the increase in soil exposure at 7-21 C. This area also provides non-forested recreation and parking areas adjacent to the lake. These locations follow the expected spectra for construction and development areas (Table 7-1).

Much of the vegetation in tracts on the eastern side of the lake around these circled areas are pine stands and therefore reveals a trajectory of mesic/other (pine) in 1972 to mesic/other (pine) in 1992. The tracts on the western side of the lake reveal the same spectral trajectory as other protected places in the Hoosier—a gradual transition from more xeric vegetation (red) to more mesic/xeric in green.

The change map for this area (Figure 7-22) and the forest dynamics summary chart (Figure 7-21) support these conclusions. Like the example shown in the Deam Wilderness analysis with the DEM, much of the xeric vegetation in 1972 has remained xeric in 1992 due to topography. The region identified in Figure 7-22 A, for example, is a larger summit area within one of the tracts. These 1972 and 1992 MSS color composite thumbnails (R4, G2, B1) reveal a consistently high reflectance in infrared band 4 over time. As Figure 7-23 shows, some of the former xeric vegetation is shifting toward mesic/xeric properties and much of the mesic/xeric vegetation is moving toward mesic properties. This generally follows what we would expect to see in natural regeneration but it also adds some analytic complications which will be discussed later. Overall, YW Hypothesis 1 is supported.

Figure 7-24 displays the tracts that satisfy the conditions for YW Hypothesis 2. These tract boundaries are overlaid on the 9/30/72 and 9/28/92 MSS color composite maps (R4, G2, B1) for the region. Figure 7-25 presents the SMA endmember classification maps for these tracts and Figure 7-26 provides the classification change map for this area. Like Hoosier's multiple use 2.8 designated area, the Yellowwood property covers a significant amount of land (see Figure 4-8) making interpretation of these maps difficult. Like previous analyses, the forest dynamics depicted on the change map are summarized in Figure 7-27.

Surprisingly, these tracts exhibit similar signs of natural regeneration as seen in the Hoosier area analyses. This is the most obvious aspect of change that can be identified when visually inspecting the side-by-side classification maps and the classification change map. Overall, the Yellowwood landscape gained 14 percent in mesic looking vegetation over this 20 year period (Figure 7-27). And like other areas studied, most of this gain came from vegetation that was classified as xeric or mesic/xeric in 1972.

Based on the earlier findings in Morgan-Monroe (Table 7-1), YW Hypothesis 2 expects a larger number of pixels moving from either: (1) a high xeric to high xeric if the cut occurred after 1985 (dashed arrow labeled "A" in Figure 7-27); (2) medium xeric to medium xeric if the cut occurred between 1972 and 1985 (translated to a mesic/xeric look for both years and is shown by the dashed arrow labeled "B" in Figure 7-27); and (3) high xeric to medium xeric (either more mesic or more mesic/xeric) if the cut occurred prior to 1972 (the two dashed arrows labeled "C1" and "C2" in Figure 7-27). Even with a classification change map in Figure 7-26, it is difficult if not impossible to discern these change trajectories. But the forest dynamics summary, when compared to other regions we have already studied in Hoosier and Yellowwood, reveals some very interesting patterns. If we concentrate on the percentages assigned to the four dashed arrows representing the different cutting trajectories and compare them to the other areas studied, it becomes apparent that Yellowwood exhibits higher percentages of conversion in these trajectories than other areas previously studied.

For instance, 25% of Yellowwood tracts that are candidates for timber production exhibit a high xeric to high xeric change trajectory (dashed line A in Figure 7-27), the pattern that is taken when timber has been cut after 1985 (Table 7-1). It should be emphasized that this is also the pattern taken on in locations that exhibit xeric environmental conditions. But given that Yellowwood and Hoosier fall under the same topographic conditions—what Homoya (1997) labels the "Brown County hill region"—the topographic differences between Hoosier and Yellowwood are not expected to be extreme. If this spectral trajectory was due to topographic conditions alone, we would expect Hoosier and Yellowwood areas to be relatively equal in percentage for this change category.[12] Yellowwood is higher when compared with each of the Hoosier areas, which provides strong evidence that cutting did occur between 1985 and 1992 in the region. Yellowwood also exhibits the highest percentage changing from xeric to mesic/xeric (12%) and xeric to mesic (10%) than any of the Hoosier regions studied. These two trajectories are consistent with what was found in Chapter 6 related to cutting activities conducted prior to 1972. These trajectories also can also be attributed to naturally produced circumstances, such as a young forest region that results from tornado damage, but it is doubtful that natural influences alone would make Yellowwood exhibit the highest percentages of all areas studied. Given the institutional history of Yellowwood, these are the expected patterns of change. The high percentages changing from xeric to mesic/xeric and xeric to mesic provide evidence that cutting occurred in the early 1970s, which lends support to YW Hypothesis 2 and the HPRU-YW hypothesis. Finally, the trajectory of medium xeric to medium xeric (dashed arrow B in Figure 7-27), describing cutting trajectories occurring between 1972 and 1985, provides weak evidence to support these hypotheses. While this follows the expected trajectory, I label it "weak support" because the non-cutting intensive recreation areas of Hoosier and Yellowwood also exhibit similar percentages of change along these trajectories.

In short, the results from this research lend some support to the last two hypotheses. Many of the pixels falling within "potential timber" tracts of Yellowwood do exhibit spectral trajectories similar to what was discovered in cut areas in Morgan-Monroe. Moreover, the prevalence of cutting spectral trajectories is higher in Yellowwood than anywhere in Hoosier. But these patterns are difficult to identify and they also can be produced in some natural regeneration circumstances. For this reason, I can only report with a relatively low degree of confidence that these hypotheses appear to be confirmed.

Discussion

This chapter concludes the second study of this dissertation The task at hand, then, is not only to discuss the findings related to the content in this chapter but also to link these findings to initial questions and issues raised in earlier chapters Recall in both Chapter 1 and Chapter 3 several empirical and methodological questions were presented related to this study Let me discuss the general findings of this chapter and relate them back to the empirical questions raised earlier. I will conclude with methodological implications of the study

Substantive Findings

HPRU Hypotheses 1, 2 and 3 and YW Hypothesis 1 were confirmed Areas subject to higher level of activity restrictions reveal patterns of natural regrowth Areas managed for human recreation exhibit a higher level of development patterns but also show patterns of natural regrowth over time. At a landscape level, the spectral trajectories for protected areas are consistent with the ones found in the Morgan-Monroe reference forest for protected and maturing forest areas The spectral trajectories in recreation areas were also consistent with what the Morgan-Monroe analysis identified and also with what we would theoretically expect.

The testing for timber commodity activities, HPRU Hypothesis 4, YW Hypothesis 2 and the comparison hypothesis HPRU-YW 1 provide mixed results This analysis found few signs of timber harvesting in the "multiple use" area of Hoosier's Pleasant Run Unit. It was expected that cutting would be limited there given public pressures but it was surprising how few areas were actually identified in the analysis There was, however, some evidence supporting the contention that timber cutting has been conducted in

Yellowwood over the 1972-1992 time period. The results do follow what the hypotheses suggest. I expected to find signs of cutting in Yellowwood given the incentive structure established by State Legislation described in Chapter 4. I also expected fewer signs of cutting in the area designated 2.8 in the Hoosier Pleasant Run Unit because of the added costs property managers incur related to public relations activities. But from this analysis I am not ready to say conclusively that these findings confirm the last two hypotheses. My reasons for making this statement relate to the methods used. Before addressing this issue more deeply, let me first turn to finishing the substantive discussion and answer the empirical questions posed at the beginning of this study in Chapter 3.

Where has change occurred (Empirical Question *E1* in Chapter 3)? The analysis shows that to a large degree both the National and State Forests are exhibiting similar change as captured by Landsat MSS satellite sensors. They both, in general, exhibit broad signs of forests that are maturing. The analysis, however, shows that the institutional landscape does play an important role in determining how the land cover changes. For example, the designated high recreation areas reveal different levels of soil spectra than areas designated for protection. This study also proved that cutting activities can be identified using MSS and appear to be more prevalent within the institutional landscape governing State Forest property.

How then do these findings influence policy issues (Question *E1*)? It provides some evidence to support statements made by officials of the Forest Service and the Indiana Division of Forestry in regard to their timber-cutting activities. From a satellite perspective, their forests appear to be, on the whole, growing older. It was surprising to find that in every institutionally bounded area, regardless of institutional composition, the forest appears to becoming more mesic-looking over time. The findings related to cutting in Chapter 6 link mesic spectra to older forest stands in the deciduous forests of Indiana. If a mesic looking spectra is in fact linked to older age classes as this and other research (Green, 1988, 1996) suggest, then it appears that from a landscape perspective, the harvesting property managers are undertaking in these forests are not at all out competing natural regrowth. Forest stands everywhere, under all institutional configurations are becoming, in general, older. This finding should please forest officials for it provides support that their annual allowable cut policies are allowing their forests as a whole to age gracefully.

What direct actions have contributed to the change we witness in these forested properties (Question *E2*)? The analysis in this chapter and Chapters 4 and 6 fully addressed this question. The types of activities undertaken are listed in Tables 4-1, 4-2 and 4-3.

What are the indirect forces that lead humans to undertake certain activities (Question *E3*)? These too were addressed in detail in Chapter 4. The findings in this chapter confirm that stable or changing institutional landscapes supported by U.S.'s well defined system of property rights and strong monitoring systems are instrumental in determining how humans act on the ground and how land cover changes or remains stable. The findings here also find that the multiple use institutions in both the State and National Forest systems are producing actions that yield overall older growth forests.

What temporal patterns in community and/or institutional landscapes appear to have led to resource conditions we might consider "positive" or "negative" (Question *E4*)? It is clear that the rather stable institutional landscape around the Deam Wilderness area has produced clear results where the forest vegetation has rapidly replaced areas that exhibited soil exposure. What is even more apparent from this research is that over the longer time period (beyond the time frame captured by satellite images) the success of the National and State Forest initiatives in Indiana has revitalized a landscape that 60-70 years ago was in very poor condition. Over the long term the shift from private to public ownership has produced remarkable results in terms of forest resource regrowth in these regions of Indiana. This statement is not suggesting that public management is the only way to go: Many private and communal forests in the region are also regenerating (see for example, Gibson and Koontz, 1998). However, when one considers the longer term history (1920s-present day) of farm abandonment, the CCC initiatives to protect eroding land, public purchase and management, and then examines the forests that exist today, it is a rather remarkable example of forest institutions that have produced in significant forest regrowth.

This study supports the contention that humans take actions in response to incentive structures. The analysis in Chapter 4 revealed that State Forest property managers find themselves under more legislation-established incentives emphasizing forest harvesting activities than do National Forest officials. The tentative findings related to HPRU Hypothesis 3, YW Hypothesis 2 and HPRU-YW Hypothesis 1 in this chapter tend to support this conclusion. Some citizen groups are actively raising concerns over the use of public forests for timber production purposes. Others take the opposite stance and argue that these are renewable resources that should be used to help improve or maintain the economic condition of nearby counties and the State. Regardless of where the reader falls on this argument, this study argues that it is the incentive structure *established by legislation* that is the primary factor driving the decision-making behavior of public managers. The budgetary incentives, such as the dedicated fund in the case of the State Forests, are established in Indiana State Code. The elected officials maintain the State or National laws and these are the people who need to be challenged if someone disagrees with the actions property managers are taking.

Methodological implications

Let me first reflect on issues related to this particular chapter and then move to answering the methodological questions raised in Chapter 1 and 3.

Good researchers must be skeptical of results and must work to achieve a high level of confidence that the results they report are correct. I have not yet reached a high enough level of confidence related to the findings on cutting activities (HPRU Hypothesis 4, YW Hypothesis 2, HPRU-YW Hypothesis 1) to feel strongly confident that these results are correct. I have learned from this analysis that the spectral trajectories of cutting—in other words, forest age class—are complex and more work needs to be done to understand these complexities. Recall that the primary goal of Chapter 6 was to prove that Landsat MSS had good enough spectral and spatial resolution to pick up human produced cutting activities. To achieve that goal I made a critical decision: *I evaluated cutting locations that were fully illuminated by the sun to make sure the spectral trajectories I produced were true and not artifacts of shadowing*. This was a crucial and absolutely necessary step to confirm that MSS was capable of capturing human cutting activities. From this, I believe strongly that the analysis in Chapter 6 proves that MSS images are sensitive to many forest disturbance activities humans undertake in deciduous forest landscapes in the Midwestern United States.

But Chapter 6 did not provide a complete analysis of cutting locations across various topographic gradients and lighting geometries. The broader analysis undertaken in this chapter led to the conclusion that this task is necessary and critical to carefully understand lighting geometry issues if we hope to link human incentives to outcomes at the landscape level. Let me provide a clear example of why what I just said is so important for the human dimensions of global change research program.

Figure 7-28 shows three known clearcut regions in the Hoosier National Forest and provides an excellent example of the problem I wish to emphasize. The general boundaries of these clearcut areas are overlaid on the topographic map of the area (labeled "A") and color composites (R4, G2, B1) of each of the three time point MSS images (labeled B, C and D in temporal order). First review clearcut labeled #1 across the three time points and on the topographic map. Recall that for south-central Indiana, the Landsat satellite always acquires the image somewhere around 10:00 AM (Bloomington, Indiana time) when the sun is in a low southeast position in the sky. This lighting geometry then is consistent across all three images and usually illuminates southeast facing slopes and summits while causing shadow to be thrown on areas facing other directions. Notice how the rolling hills can be seen in the 1972 and 1992 images of Figure 7-28. Recall the discussion in Chapter 6 about how these features are less distinguishable in 1985 because of the high rainfall during and prior to that year making everything look more mesic (darker).

Now, notice how clearcut #1 is a darker red in 1972, a much brighter red in 1985 and then a bit darker again in 1992. This is the spectral trajectory we would expect for a cut that occurred between 1972 and 1985 (Table 7-1), which is in fact what occurred. The reason why this is consistent with what we would expect is because cut #1 occurred on a largely southeast facing slope and valley (see the topographic map, Figure 7-28 A). Therefore, the cut is well lit by the early morning sun. However, if we compare the spectral trajectories of cuts #2 and #3 in Figure 7-28 we see that they show some signs of mesic-xeric-mesic trajectories but much less apparent than cut #1. Their reflectance data provides a darker look in this composite. Cut #2 falls on a generally west-facing slope while cut #3 falls on a southwest-facing slope. One reason for the darker appearance can be attributed to shadow that is projected by taller adjacent stands that are blocking the southeast sunlight. This poses problems for analysts trying to identify human cutting activities in rolling, hilly terrains for there are shadow effects that cannot be removed through topographic normalization.

Where then does this leave us? There are two possible solutions. First, there are ratioing procedures that may be more successful in removing the effects of shadowing (Green, 1997). These ratios move the data out of physical reflectance space, which is why I avoided using them. But it is a technique that may help in removing the shadowing produced by neighboring taller stands on slopes facing away from the sun. Second, moving from an analysis based on MSS to a TM time series will help immensely. Recall that six bands of TM will provide five endmembers. We would then be able to specify shadow as an additional endmember which then would pick up the effects that are muddling this analysis. The additional two endmembers TM provides coupled with techniques to clip out land cover areas that are not of interest for analysis (e.g., water) will go a long way to improve the analysis techniques developed here and should overcome this shadowing problem. Let me now move on and address the questions posed in the introductory chapter for this study (Chapter 3).

M2)[13] To what degree can the longer temporal extent Landsat MSS data help in understanding change in forested landscapes over time?

This study shows that MSS images are informative. In my opinion, analysts have turned to other more recent technologies, in part, because they are a "hotter" technology. For example, researchers of late are turning to "hyperspectral" images (images with many sensors that capture many areas along the electromagnetic spectrum) and to a large degree have forgotten these older MSS images. While I agree that MSS has legitimate limitations in terms of spatial and spectral resolution, these images still are an important data resource that global change researchers and policy-makers should not ignore. We are at a risk of losing many of these important historical pieces of information as they sit and deteriorate on old 9-track tapes in storage. Simply put, if we are interested in the human dimensions of landscape change we should make every effort to maximize the temporal range of the study so that we do not under sample forest response to human activities (refer back to the discussion of image sampling in Chapter 6). This means we must include MSS as part of our studies.

Part of the problem related to the use of MSS is that it is not well documented—at least in a form accessible to the general human dimensions of environmental change research community—on how to calibrate these images to at-earth reflectance. I spent more than six months working with my colleague, Glen Green, figuring out the appropriate procedures to calibrate these images. We have developed spreadsheets that do most of the math that allow the researcher to calibrate these images regardless of whether it came from EROS data center with a header or not. In short, one of the contributions this dissertation has made is to determine how these calibration procedures are done and then documenting these procedures for others (see also Green, Schweik and Hanson, 1998) These procedures make it easier to calibrate MSS data to at-surface reflectance which open up opportunities for their use in comparative studies with other locations

This study took on another great challenge related to the use of MSS by undertaking a change analysis of forested landscapes that are subject to relatively small spatial scale human disturbances For example, the silviculture practice of choice in Yellowwood is group selection cutting or sometimes single tree selection cutting—practices that disturb a forest canopy the least (See Figure 4-1) One of the goals of the property manager is to maintain a relatively mature forest canopy which makes identifying actions difficult. But through the use of the subpixel spectral mixture analysis technique this analysis *did*, however, produce results consistent with expectations. I believe this in itself justifies the use of MSS images for global change studies

Finally, I am certain that the payoff of using a MSS time series will be greater in locations where forest change is more dramatic. The recreation area studies revealed consistent results related to forest-soil changes where changes in light reflectance are dramatic. Analyses that employ MSS for other locations in the world where forests are subject to significant levels of human induced deforestation will identify where forests are being replaced by soil and vice versa and are certain to yield dramatic results.

M3) How can we tease out the effects of human activities from patterns in temporal sets of satellite imagery?

In this set of chapters related to this study, I have tried to apply a careful and systematic approach to the study of human incentives, actions and outcomes. I think the approach here provides a useful model of how a researcher might work to tease out the effects of human activities In short, from this experience other researchers undertaking similar work would be wise to

(1) Investigate and document the incentive structures that drive human actions in the context he or she is interested in studying.

(2) Inventory the suite of potential activity choices that humans in the area might undertake;

(3) Consider the temporal resolution of the land cover disturbances these activities will produce and select enough images to "critically sample" the phenomenon of interest,

(4) Control for season and weather effects through a careful selection of satellite images;

(5) Identify a subset of locations where these actions have occurred and investigate how these have influenced the physical spectral response in the time series images;

(6) Control for topographic effects through the use of GIS products such as a digital elevation model or a scanned georeferenced topographic map or worst case, account for these effects through awareness and a visual interpretation of the images,

and, ideally,

(7) Convert the multispectral images from at-satellite digital numbers to at-surface reflectance so that the study's findings can be compared with other studies of similar forest types.

In addition to developing this approach, this study also exhibits some new methods for exploring incentives to actions to outcomes using GIS and satellite images. Chapter 6 provides an example of how we can carefully analyze the effects human actions have on forests as measured by multispectral images. Chapter 4 along with Chapter 7 provide an example of how we can study the broader institutional landscape and its effect on the behavior of humans interacting within the forest The Hoosier study here is the first study I have seen that applies GIS to map and study the effects of a changing institutional landscape on human behavior and forest outcomes We all are very much aware of how landscapes all over the world are subjected to changing rules that have geographic properties and the approach I have taken here, I believe, provides an important example on how we might begin to study these phenomena. This may be this study's most important contribution

M4) To what degree does the analytic technique spectral mixture analysis (Adams, et al., 1994) help to understand change that has occurred at a relatively course spatial resolution MSS imagery?

Another important contribution made by this second study of the dissertation is the development of an initial forest classification system using multispectral satellite images that are based on physical measurements of reflectance rather than the raw digital numbers that come on unprocessed satellite images. With image data representing at-earth reflectance, I was able to establish the beginning of a "spectral library" of at-surface reflectance of "pure" land cover types (endmembers) in the south-central area. With this endmember library created, SMA could be applied to conduct a "subpixel" analysis and create endmember fraction images for the public forests the study was interested in. From these, I developed an initial forest classification system that *can be replicated by other researchers in other locations*. Anyone else can apply the same three endmembers I provide in Table 6-2 to their study location, and define their classification using the definitions I provide in Table 7-2. The technique used here, following efforts by Adams *et al* (1995), moves the human dimensions of global change community forward by allowing multispectral image generated classification maps of different locations but similar forest types to be directly compared—something we could not (or really should not do) without conducting image processing (see Green, Schweik and Hanson, 1998)

Admittedly, there is the three endmember limitation when applying SMA to Landsat MSS images. Having one endmember, the "mesic/other" class, capture the influence of mesic vegetation, pine and shadow is undesirable. But taking this same approach and applying it to Landsat TM with 6 bands opens up tremendous opportunities to researchers trying to scale up from the study of a one case study location to broader regions of the earth. Developing directly comparable and reproducible classification maps and linking them to human actions and incentive structures as this study has done is an important direction the global change research community should be headed if we are to understand how the earth is changing and what role humanity plays in it. Let me now turn to the final chapter which will reflect on this entire dissertation endeavor and suggest a future research program

Chapter 7 Endnotes

1. Classification maps also are helpful for analyzing change in more than three images (Adams, *et al.*, 1995). Color composites are limited to three time points for there are only the three red, green, blue "color guns" that can be applied

2. Note that the percentages are a little lower than one would expect mainly because most fraction images do not add up to 100 percent because of the RMS error being a bit higher This is a limitation in using MSS images with only 4 bands. If one applies this technique to TM images with 6 bands of data (ignoring the thermal band), the technique is expected to work even better than it does here

Also, in some instances I failed to clip out all the clouds and cloud shadow areas from the 1972 scene prior to SMA analysis (see Figure 7 1 D) Results placed these areas in an "other shadow" category where they were not explained well by any of the three endmembers For ease of reader interpretation, I decided it was appropriate to combine this "other shadow" category with the mesic, pine and shadow category

3. I could have developed even more detailed classes. For example, classes could have been defined with certain percentages of soil, xeric vegetation and mesic vegetation together However, these four classes seemed appropriate enough for the work here and kept the level of complexity reasonable in later parts of this chapter.

4 It makes some sense to analyze two time points simply for ease of readability of the figures Viewing two extreme time point classification maps in larger format side by side in figures is preferable than displaying all three in smaller sizes.

5 Pine in Indiana was planted by the Civilian Conservation Corps in the 1930s and 1940s because it was the only tree species capable of surviving in the poorly eroded soils during that time (McCleery, 1977)

6 The Lake Monroe reservoir was created sometime around 1965 by the U S. Army Corps of Engineers for water control (Simpson, 1997)

7. This suggests that it may be possible to develop a classification system using TM data and the xeric endmember that captures age classes in more depth. This will be discussed further in the conclusion of this chapter and of the dissertation.

8. This is what the Forest Service expects to happen over time. In the 1981 Plan Record of Decision, they state: "We estimate over the 150-year planning horizon the oak-hickory type will decrease by about 25 percent and the mixed deciduous hardwood type will increase about 30 percent" (USDA Forest Service, 1985c: 12). Moreover, they recognize here the value of maintaining oak-hickory type stands: "Beech and maple in southern Indiana do not provide the same quality of timber products as they do in the northern hardwood forests. Their amount and value is much less than can be obtained from the oak-hickory type"

(Ibid.: 12) This statement reveals the economic incentive for maintaining oak-hickory (more xeric) types of stands in both Hoosier and Yellowwood.

9 Provided by Professor J.C. Randolph, Director of the Midwestern Regional Center for the National Institute for Global Environmental Change

10. The number eighteen is calculated by adding the nine pixels that were soil in 1972 and remained soil in 1992 with the nine pixels that were mesic in 1972 and now are soil in 1992.

11. The tract boundaries used here are georeferenced slightly different than the MSS and TM images. The soil areas, for example are about one pixel farther north in relation to the tract boundaries. This does not cause any significant problem for analysis, just a minor inconvenience and may add a little confusion to readers familiar with Yellowwood. The important thing is that the images have been georeferenced to common ground control points with an RMS error of less than ½ a pixel. Therefore the change maps they produce are accurate.

12. This question could be investigated using the digital elevation model I believe. But just how to test this is a question too complicated for me to undertake at this juncture.

13. Recall that the first methodological question *MI* was addressed in Part I of this dissertation.

Table 7-1: Summary of Spectral Trajectories from Various Human Activities (Identified in Chapter 6)

Human Activity Related to Forest	Associated Endmember % Trajectory (including range found in Chapter 6)	Associated Chapter 6 Figure
Protected Forest	1972 **high** xeric (range 40% or above) to 1992 **lower** xeric (range 35-40%)	6-26
Construction/ Development	1972 **lower** soil (20-30%) to 1992 **higher** soil (40% or above)	6-28
Timber group selection cut after 1985	1972 **high** xeric (40-60%) to 1992 **high** xeric (40-55%)	6-30
Timber group selection cut between 1972 and 1985	1972 **medium**[1] xeric (20%-39%) to 1992 **medium** xeric (20%-35%)	6-32
Timber group selection cut before 1972	1972 **high xeric** (40-50% above) to 1992 **medium xeric** (30-39%)	6-34
Recreation areas	1972 **low** soil (< 10%) to 1992 **higher** soil (10% or greater) AND 1972 **high** xeric vegetation (>40%) to 1992 **medium** xeric vegetation (<40%)	6-35

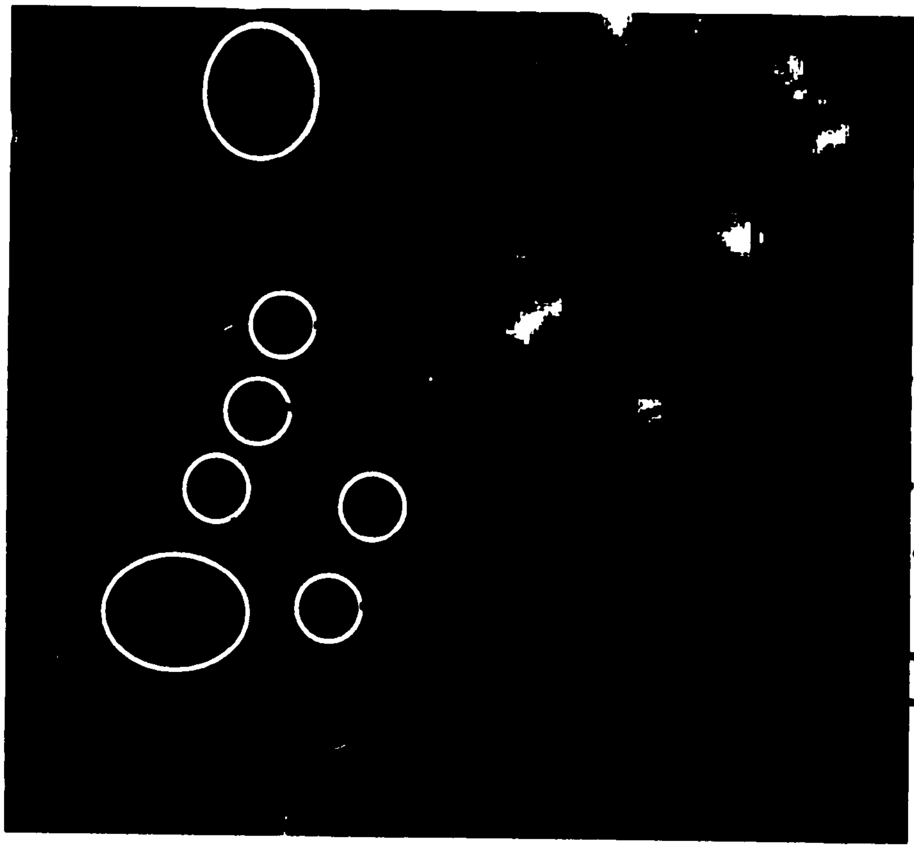
[1]"Medium" xeric vegetation is equivalent to "xeric/mesic" in this analysis.

Table 7-2: SMA Fraction Categories and Class Names

Class	Associated Number and Color	Description
Xeric Vegetation Dominated Forest	1. Red	> 40 xeric, < 40 mesic; < 40 soil
Soil Dominated	2. Gold	> 40 soil; < 40 mesic, < 40 xeric
Mixed Mesic/Xeric Forest Vegetation	3. Light Green	> 20 mesic; > 20 xeric; < 20 soil
Mesic Dominated Vegetation or Other Land Cover (e.g., Pine, Shadow, Cloud)	4. Dark Green	> 40 mesic; or doesn't satisfy the other three conditions above
Outside of the institutional landscape border	5. Gray	Outside of the institutional border area that were clipped during GIS processing

**Figure 7-1: Hoosier National Forest Deam Wilderness Area (Area 5.1)
Side by Side MSS Image Comparison (R4, G2, B1)**

9/30/72 MSS (R4, G2, B1)



9/28/92 MSS (R4, G2, B1)

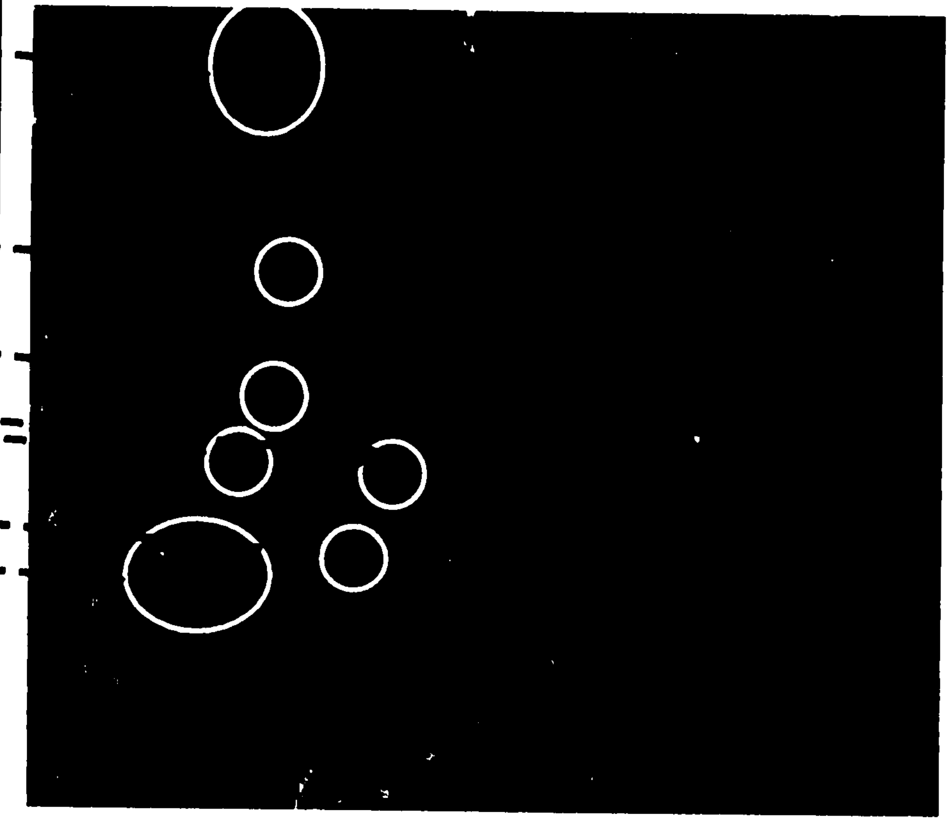


Figure 7-2: Hoosier National Forest Deam Wilderness (Area 5.1) Classification Maps

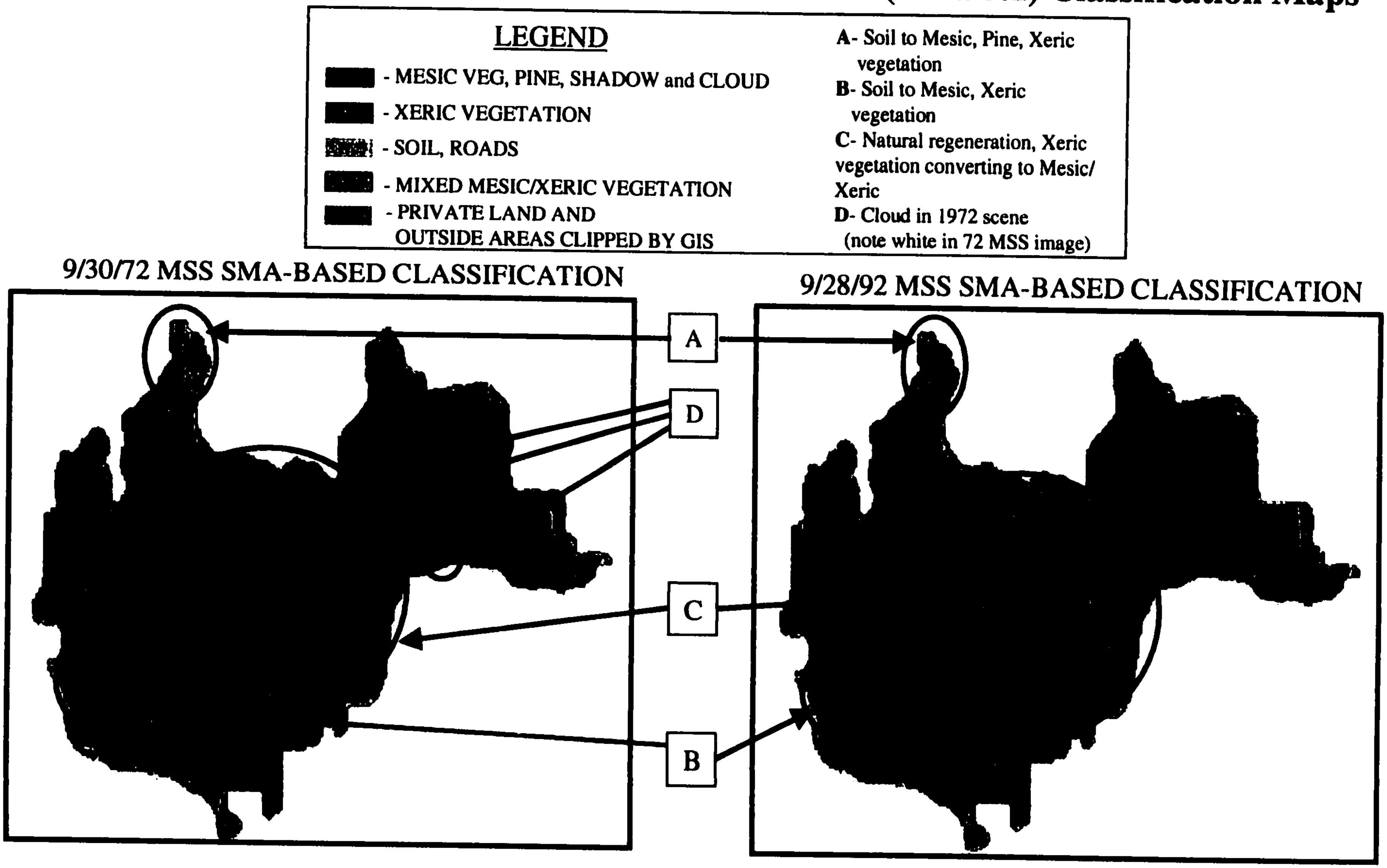


Figure 7-3: Hoosier National Forest Deam Wilderness Area (Area 5.1) 9/28/92 Classification (only xeric and mesic/xeric categories) Overlaid on Digital Elevation Model

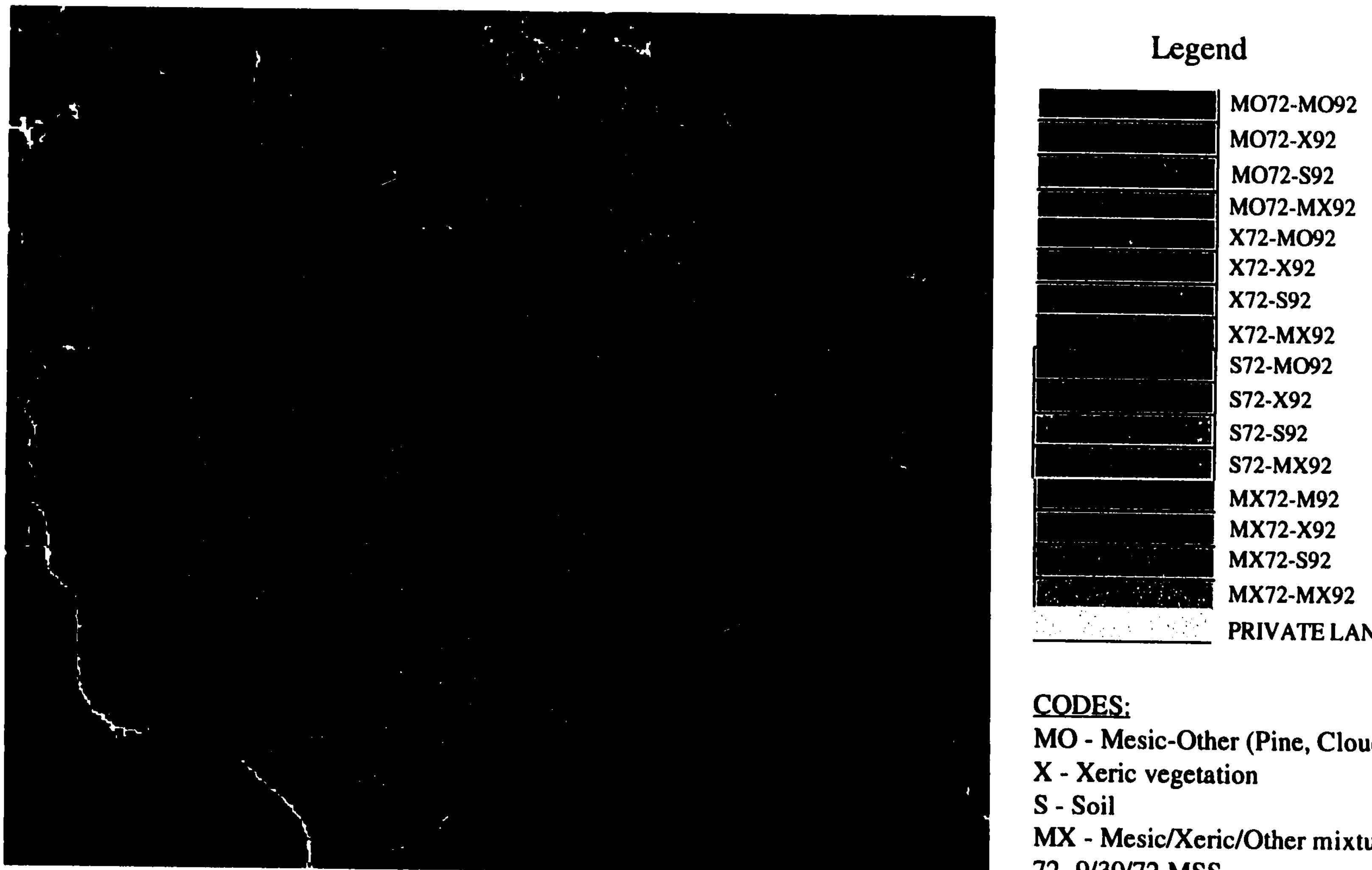
LEGEND

XERIC VEGETATION

MIXED MESIC/XERIC VEGETATION

ELEVATION DATA:
DARK-LOW; BRIGHT-HIGH

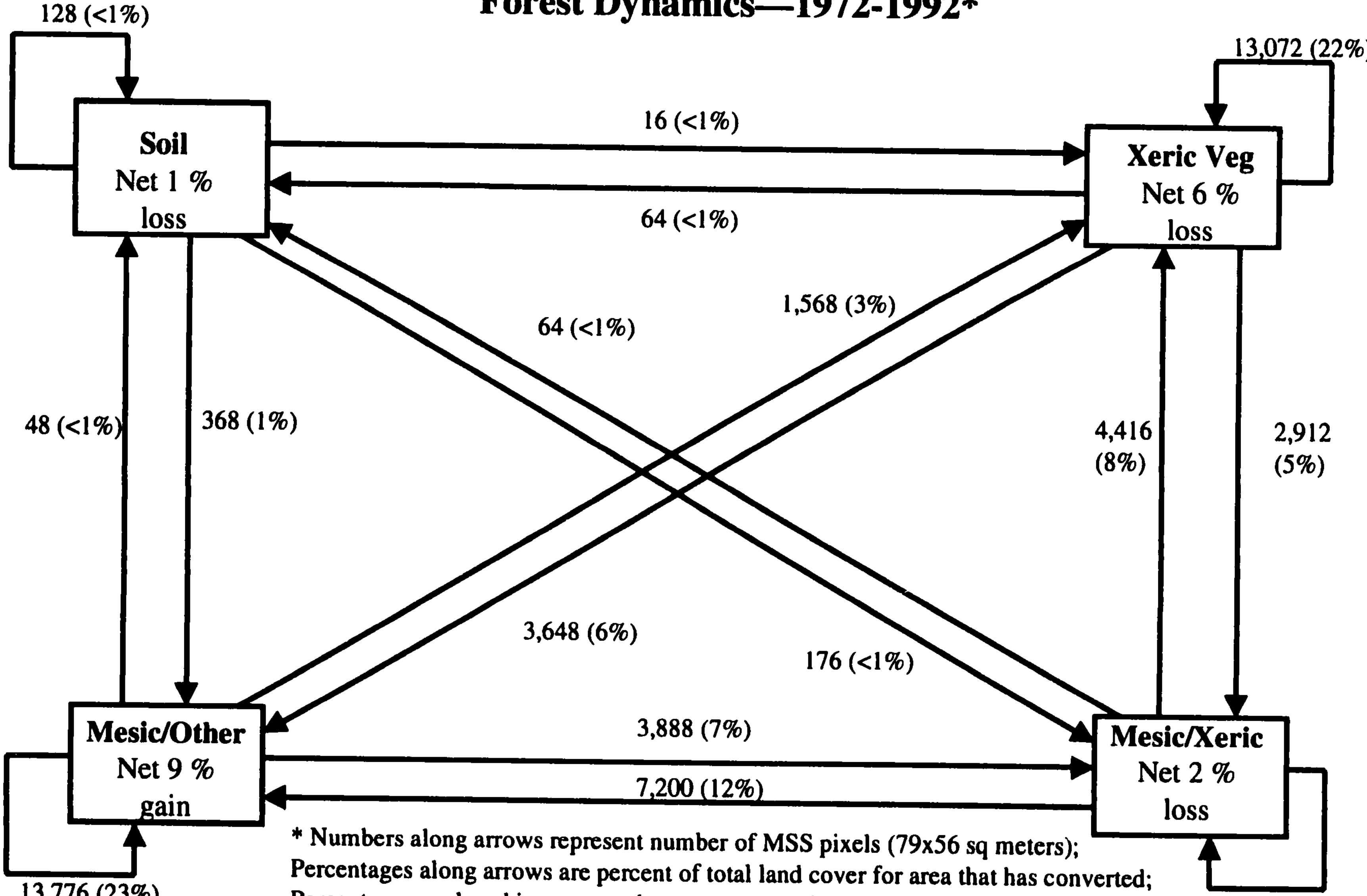
Figure 7-4: Hoosier National Forest Deam Wilderness (Area 5.1) Classification Change Map*



<u>CODES:</u>
MO - Mesic-Other (Pine, Clouds, Shadow)
X - Xeric vegetation
S - Soil
MX - Mesic/Xeric/Other mixture
72- 9/30/72 MSS
92- 9/28/92 MSS

* Background 9/97 Landsat TM color composite (R3, G2, B1)

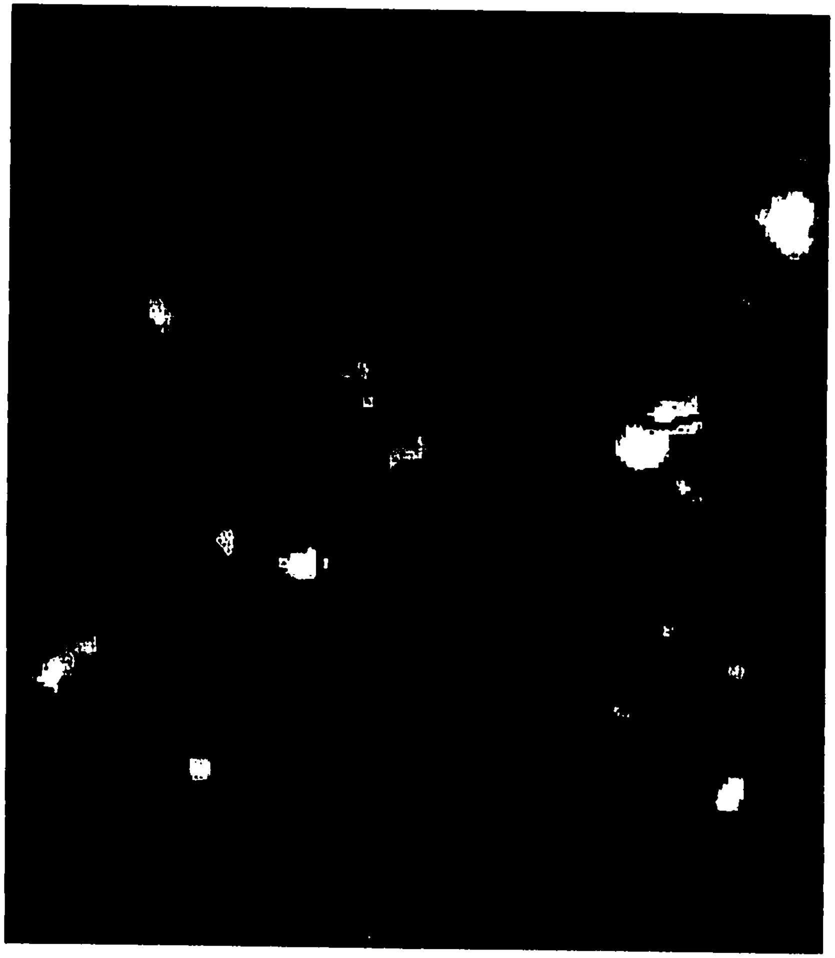
Figure 7-5: Hoosier National Forest Deam Wilderness (Area 5.1) Forest Dynamics—1972-1992*



* Numbers along arrows represent number of MSS pixels (79x56 sq meters);
Percentages along arrows are percent of total land cover for area that has converted;
Percentages enclosed in category boxes report total net loss or gain for that category.
Percentages may not total exactly due to rounding.

Figure 7-6: Hoosier National Forest Pleasant Run Unit—
Area Designated 3.2 prior to 1985, 6.1 in 1985-1990 and 6.2 in 1991
Side by Side MSS Image Comparison (R4, G2, B1)

9/30/72 MSS (R4, G2, B1)



9/28/92 MSS (R4, G2, B1)

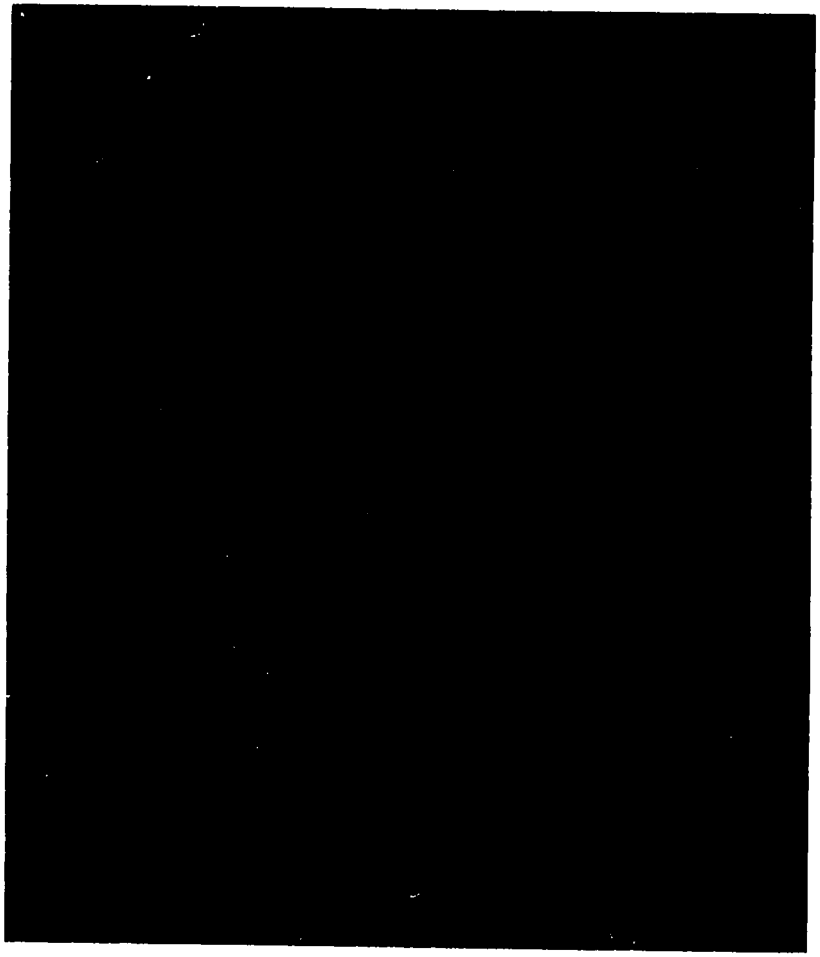


Figure 7-7: Change in the Hoosier National Forest Pleasant Run Unit— Area Designated 3.2 prior to 1985, 6.1 in 1985-1990 and 6.2 in 1991

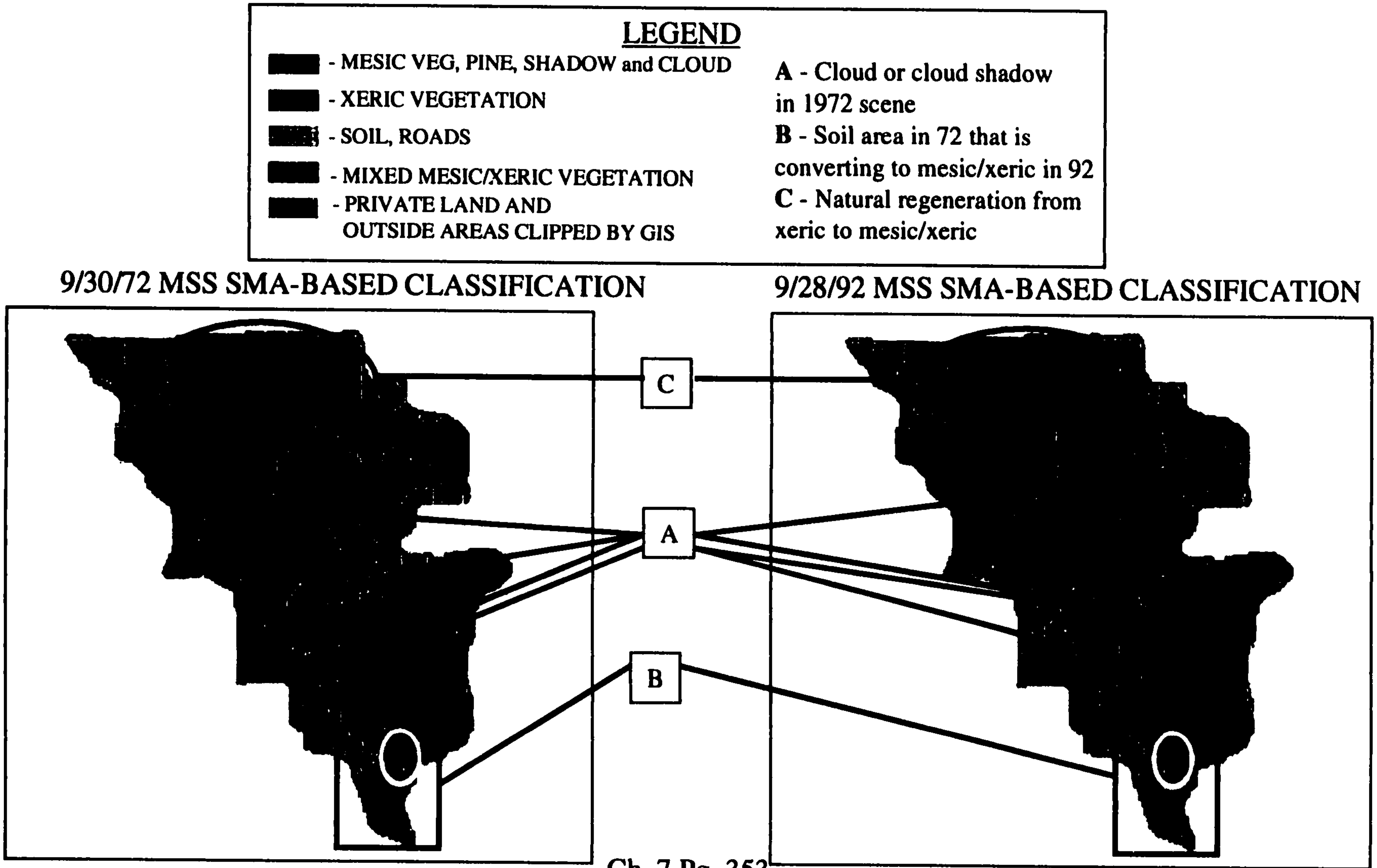
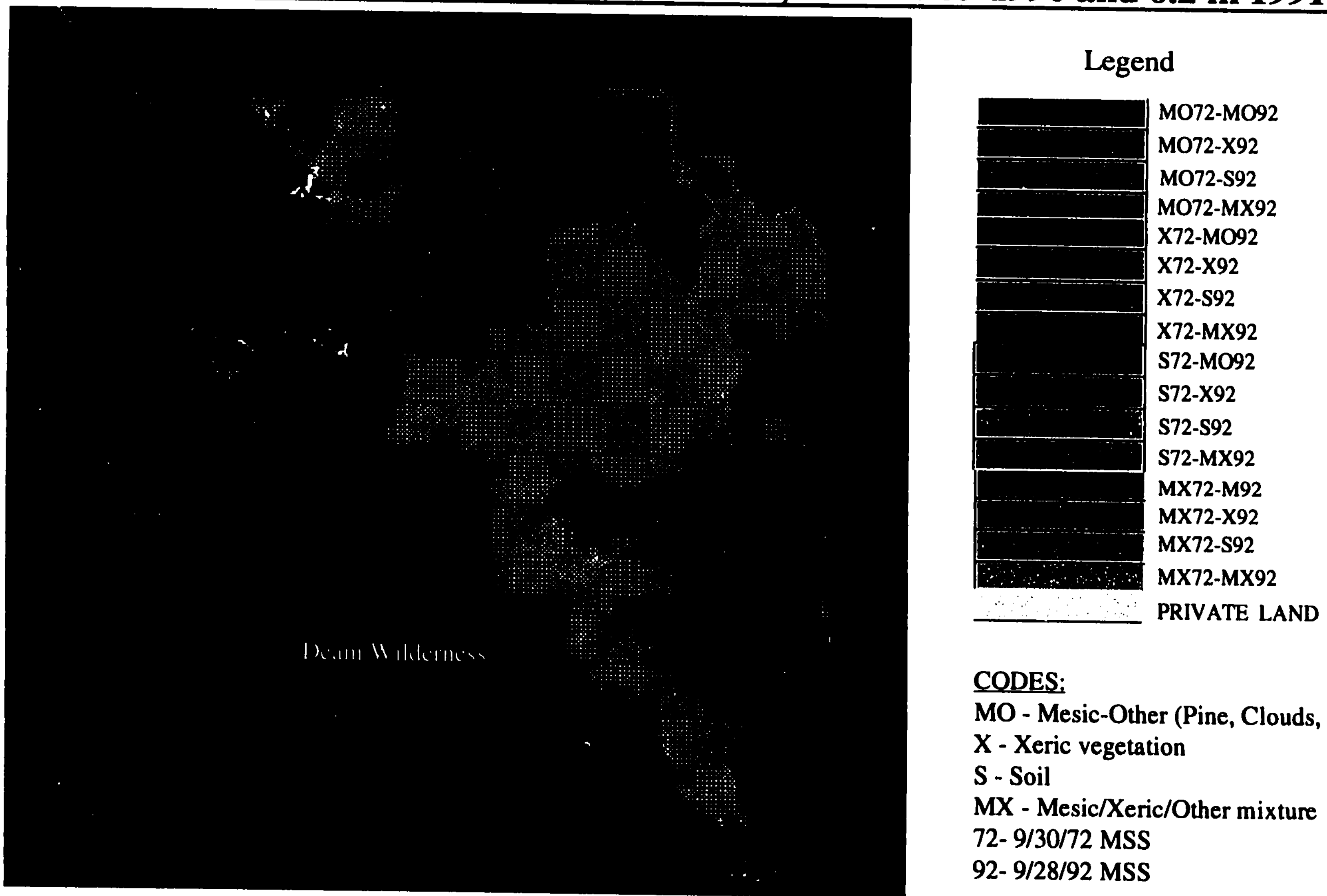


Figure 7-8: Hoosier National Forest Pleasant Run Unit—Classification Change Map for Area Designated 3.2 prior to 1985, 6.1 in 1985-1990 and 6.2 in 1991

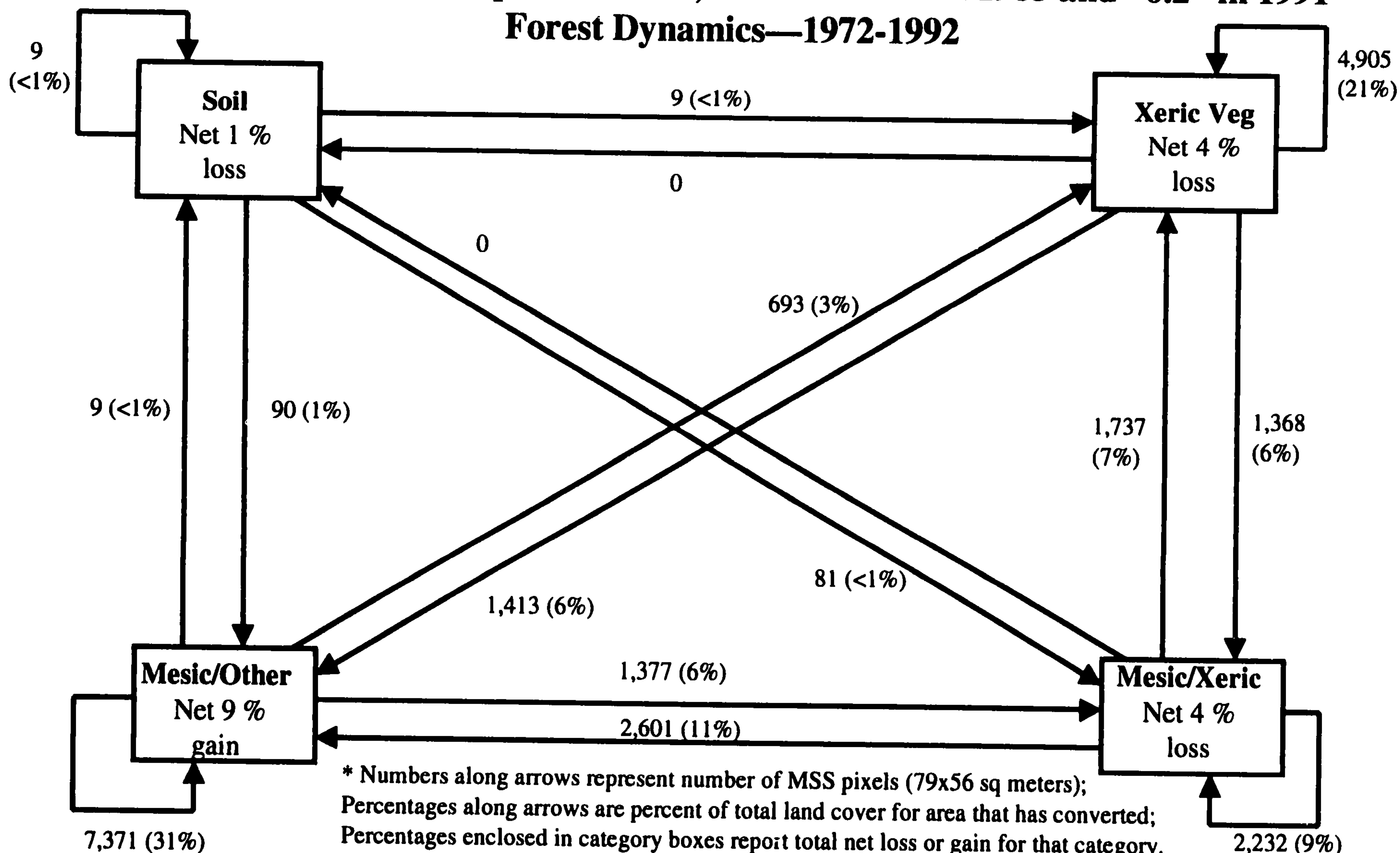


* Background 9/97 Landsat TM color composite (R3, G2, B1)

CODES:

MO - Mesic-Other (Pine, Clouds, Shadow)
X - Xeric vegetation
S - Soil
MX - Mesic/Xeric/Other mixture
72- 9/30/72 MSS
92- 9/28/92 MSS

Figure 7-9: Hoosier National Forest Area Pleasant Run Unit— Area Designated "3.2" prior to 1985, "6.1" or "8.3" in 1985 and "6.2" in 1991 Forest Dynamics—1972-1992



* Numbers along arrows represent number of MSS pixels (79x56 sq meters);
Percentages along arrows are percent of total land cover for area that has converted;
Percentages enclosed in category boxes report total net loss or gain for that category.
Percentages may not total exactly because of rounding.

Figure 7-11: Change in the Hoosier National Forest Pleasant Run Unit—Area Designated 7.1 (Intensive Recreation Area)

LEGEND

- MESIC VEG, PINE, SHADOW and CLOUD
- XERIC VEGETATION
- SOIL, ROADS
- MIXED MESIC/XERIC VEGETATION
- PRIVATE LAND AND OUTSIDE AREAS CLIPPED BY GIS

A - Soil (recreation) areas, such as picnic areas, boat launch areas. Some areas are exhibit permanent soil spectra and others are becoming hidden by tree canopies surrounding them

B - Signs of natural regeneration, xeric converting to mesic/xeric

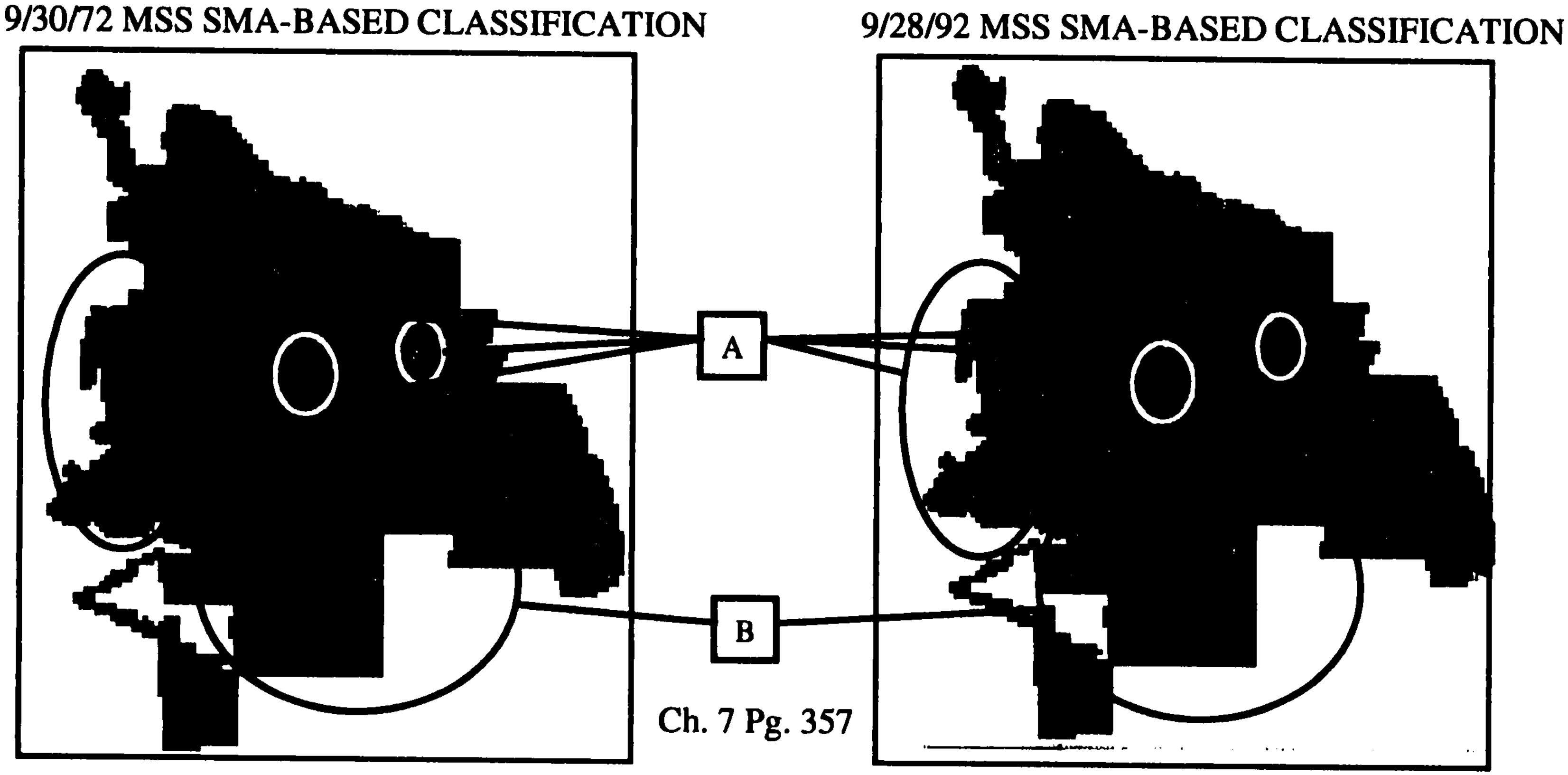
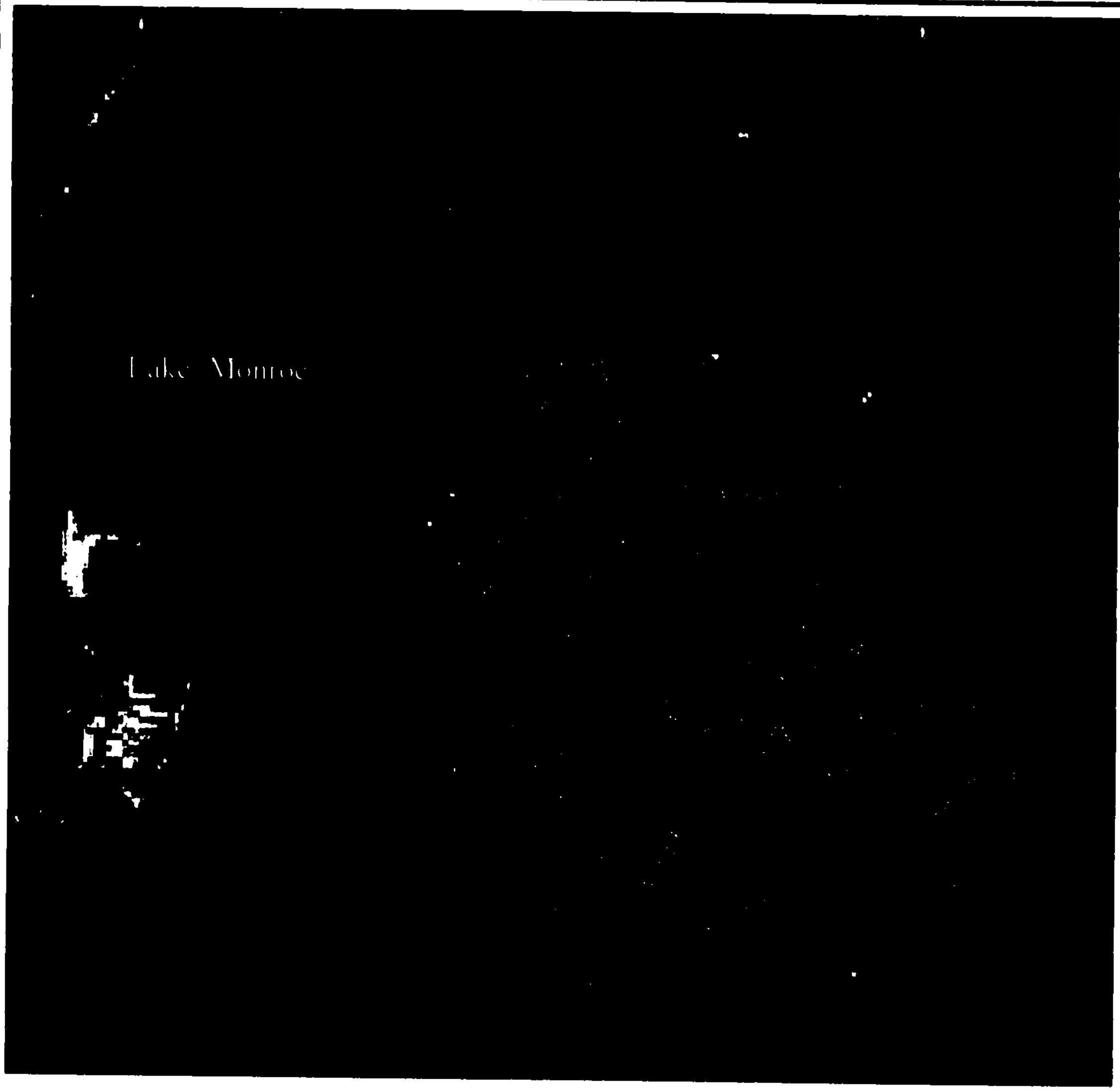


Figure 7-12: Hoosier National Forest Pleasant Run Unit—Classification Change Map for Area Designated 7.1 (Intensive Recreation Area)*



* Background 9/97 Landsat TM color composite (R3, G2, B1)

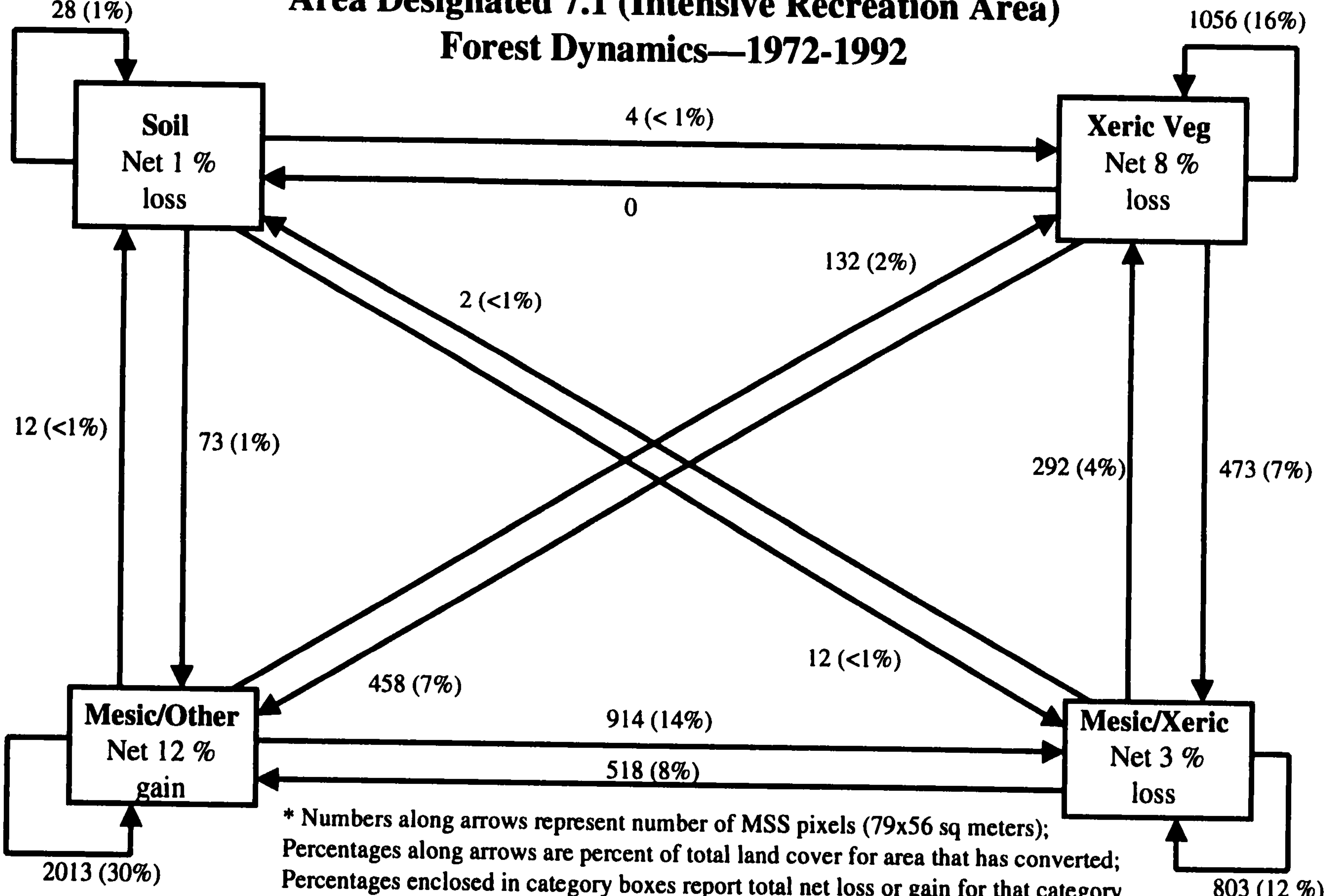
Legend

- MO72-MO92
- MO72-X92
- MO72-S92
- MO72-MX92
- X72-MO92
- X72-X92
- X72-S92
- X72-MX92
- S72-MO92
- S72-X92
- S72-S92
- S72-MX92
- MX72-M92
- MX72-X92
- MX72-S92
- MX72-MX92
- PRIVATE LAND

CODES:

MO - Mesic-Other (Pine, Clouds, Shadow)
X - Xeric vegetation
S - Soil
MX - Mesic/Xeric/Other mixture
72- 9/30/72 MSS
92- 9/28/92 MSS

Figure 7-13: Hoosier National Forest Area Pleasant Run Unit—Area Designated 7.1 (Intensive Recreation Area) Forest Dynamics—1972-1992



* Numbers along arrows represent number of MSS pixels (79x56 sq meters);
Percentages along arrows are percent of total land cover for area that has converted;
Percentages enclosed in category boxes report total net loss or gain for that category.
Percentages may not total exactly because of rounding.

Figure 7-15: Change in the Hoosier National Forest Pleasant Run Unit— Area Designated 3.1 or 3.2 in 1985 that in 1991 is 2.8 ("Multiple Use")

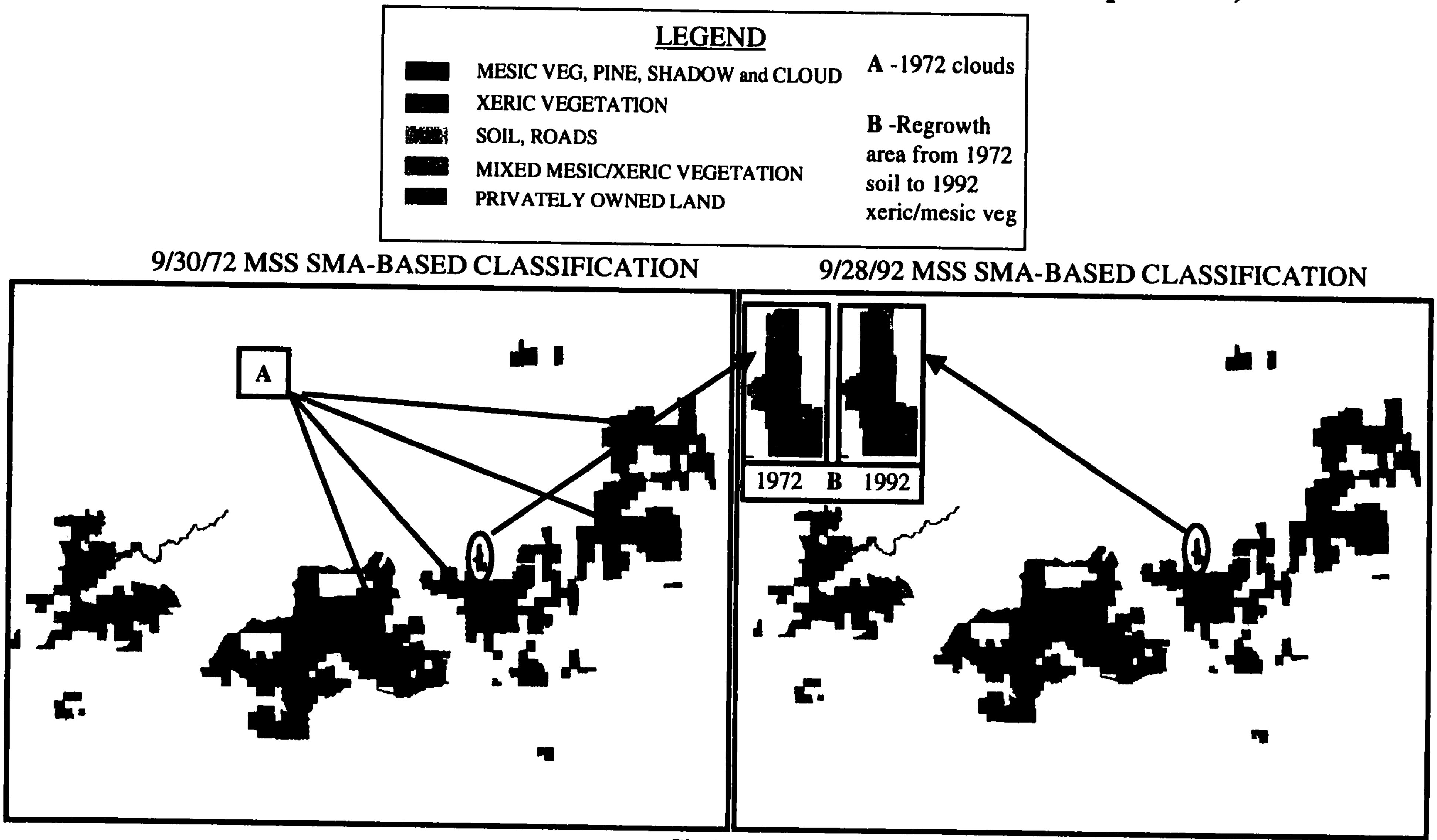
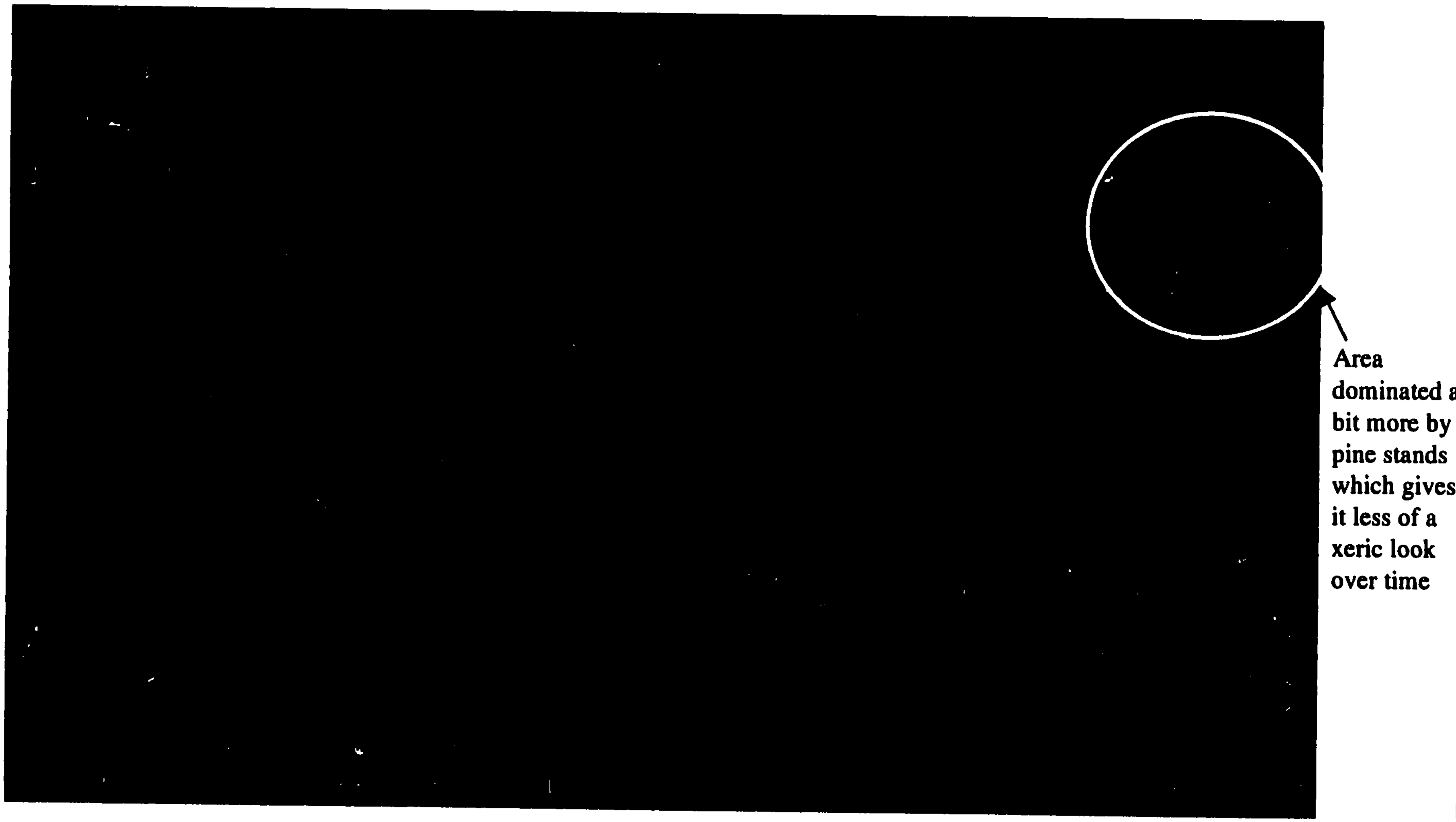


Figure 7-16: Hoosier National Forest Pleasant Run Unit—Classification Change Map for Area Designated 3.1 or 3.2 in 1985 That in 1991 is 2.8 ("Multiple Use")*



* Background 9/97 Landsat TM color composite (R3, G2, B1)

See Figure 7-9 for Legend

Figure 7-17: Example of an Area Within the Hoosier National Forest Pleasant Run Unit With 2.8 Designation That Exhibits Signs of Timber Cutting Activities

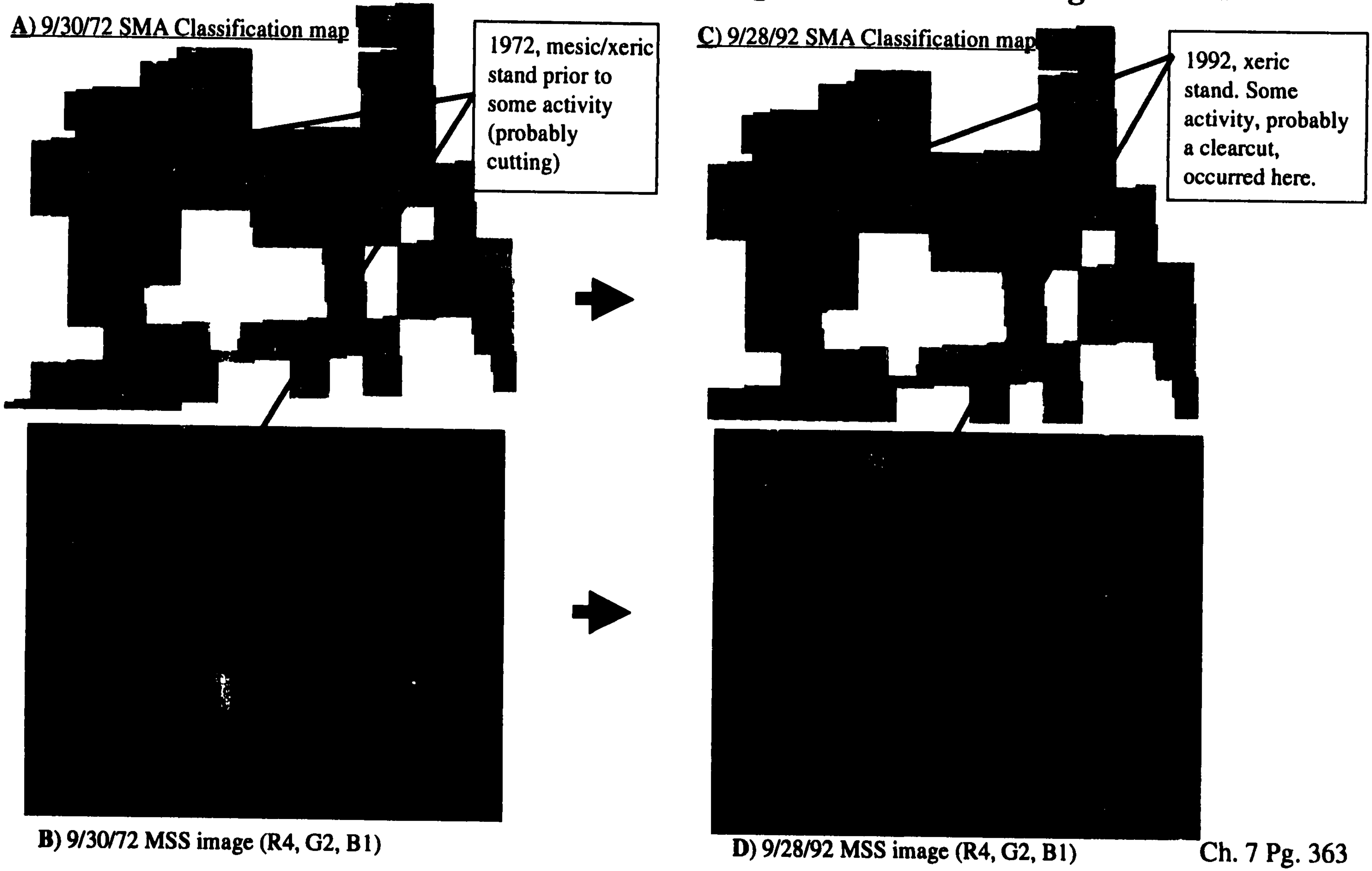
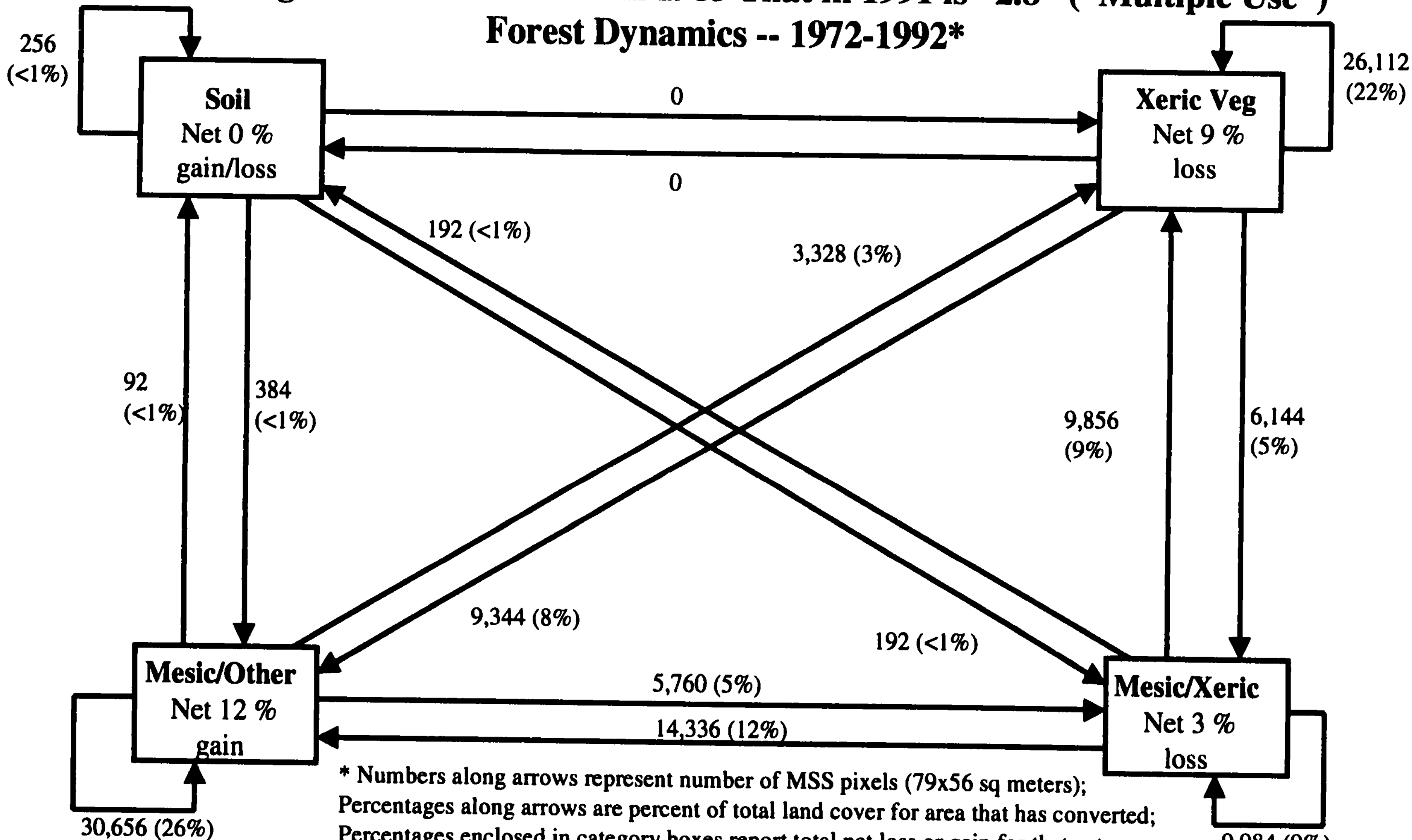
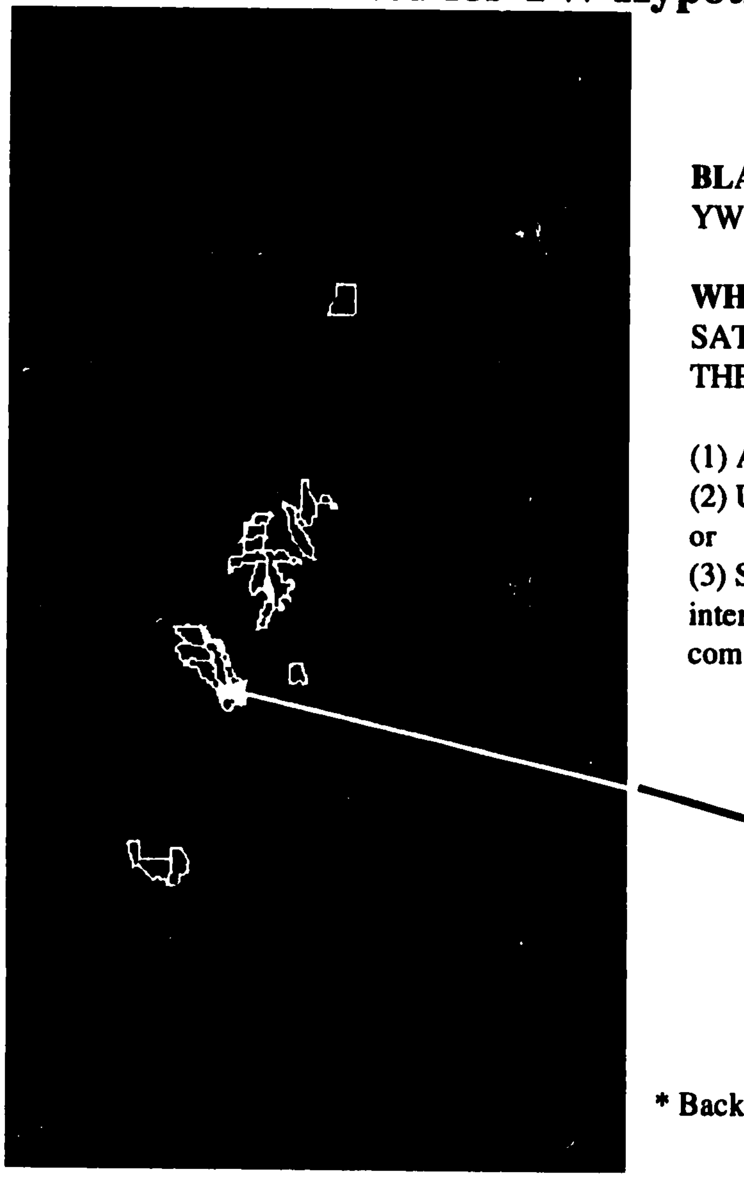


**Figure 7-18 : Hoosier National Forest Area Pleasant Run Unit—
Area Designated "3.1" or "3.2" in 1985 That in 1991 is "2.8" ("Multiple Use")
Forest Dynamics -- 1972-1992***



* Numbers along arrows represent number of MSS pixels (79x56 sq meters);
Percentages along arrows are percent of total land cover for area that has converted;
Percentages enclosed in category boxes report total net loss or gain for that category.
Percentages may not total exactly because of rounding.

Figure 7-19: Yellowwood State Forest
Tracts Selected for YW Hypothesis 1 Testing*



BLACK TRACTS -- TRACTS SATISFYING YW HYPOTHESIS 1 CRITERIA

WHITE TRACTS -- TRACTS NOT SATISFYING YW HYPOTHESIS 1. THEY EITHER ARE:

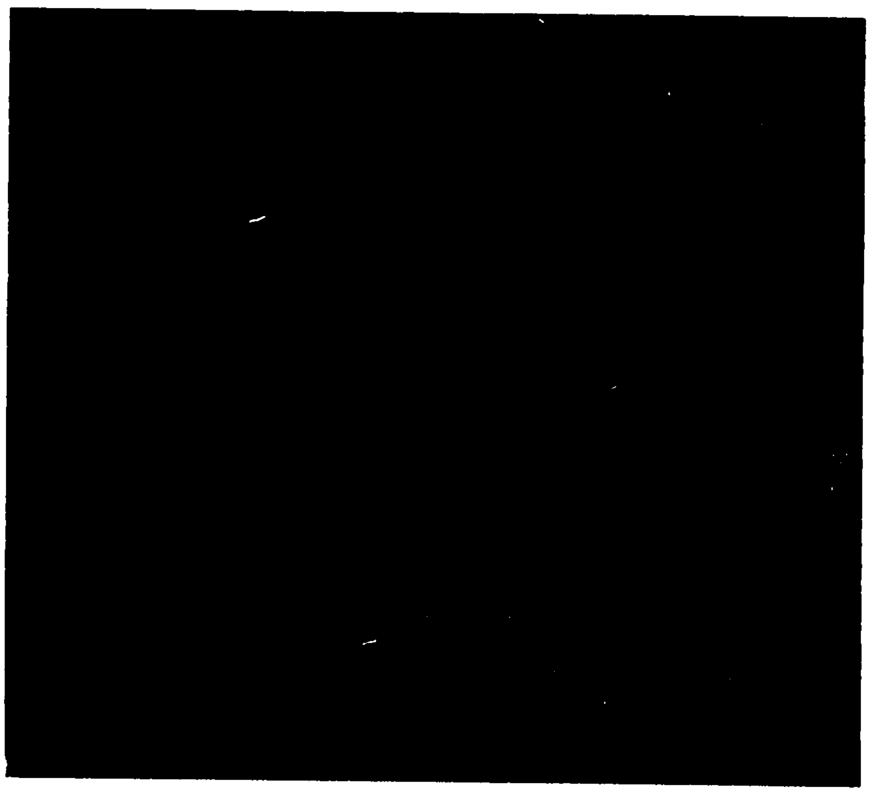
(1) Adjacent to Yellowwood Lake
(2) Used for intensive recreation (camping)
or
(3) Significant # of Pine Stands (visually interpreted from all infra-red color composite of 9/97 TM image)

* Background 9/97 Landsat TM color composite (R3, G2, B1)

Figure 7-20: Yellowwood State Forest—Tracts Bordering Lake and/or High Recreation Intensity

Side by Side MSS Image Comparison (R4, G2, B1)

9/30/72 MSS
(R4, G2, B1)



9/28/92 MSS
(R4, G2, B1)

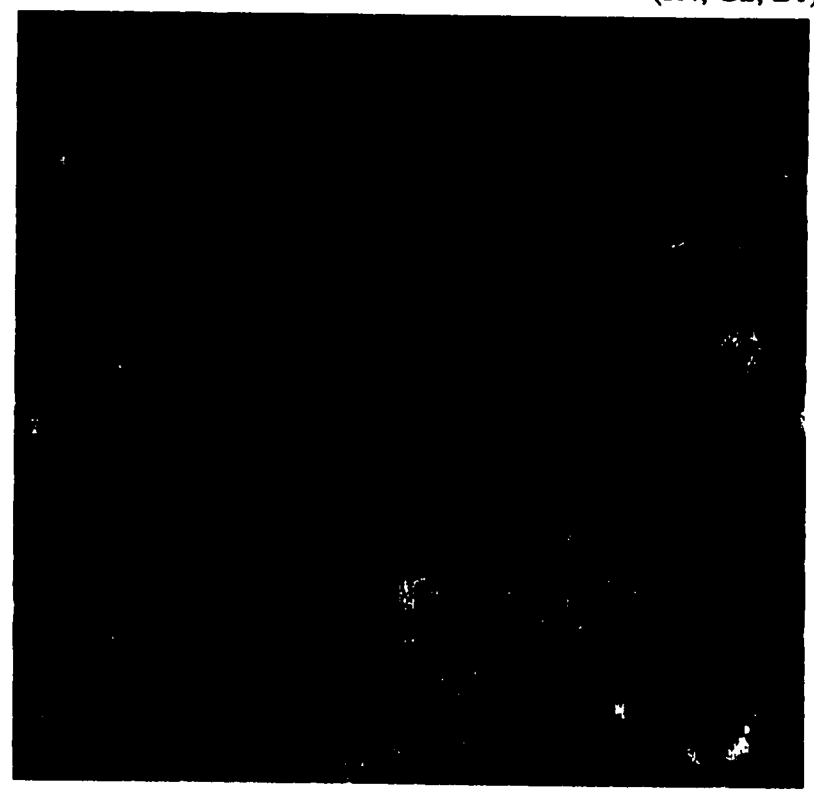
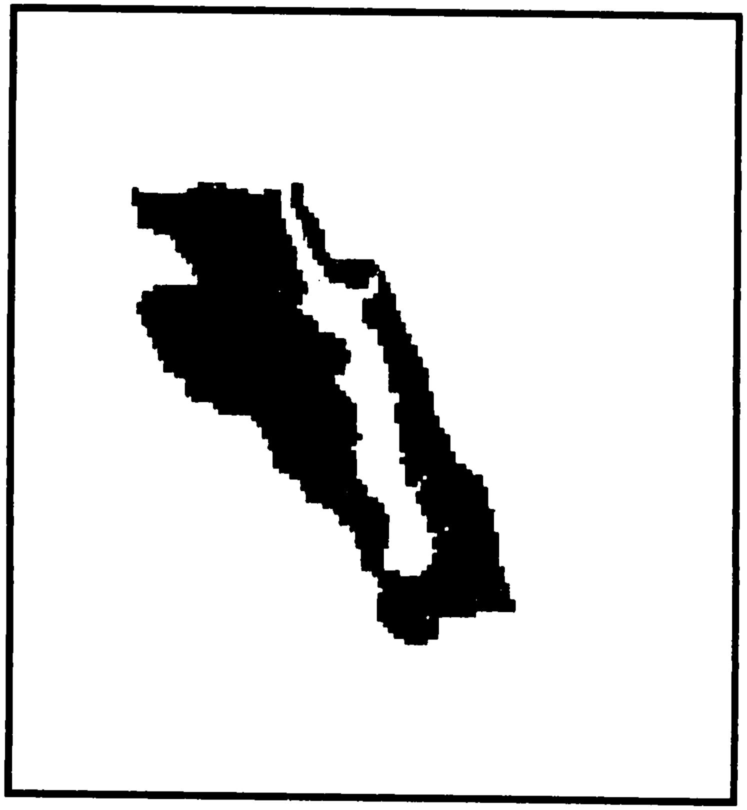


Figure 7-21: Change in the Yellowwood State Forest-Recreation and Visual Enhancement Area Tracts

LEGEND

- MESIC VEG, PINE, SHADOW and CLOUD
- XERIC VEGETATION
- SOIL, ROADS
- MIXED MESIC/XERIC VEGETATION
- PRIVATELY OWNED LAND

9/30/72 MSS SMA-BASED CLASSIFICATION



9/28/92 MSS SMA-BASED CLASSIFICATION

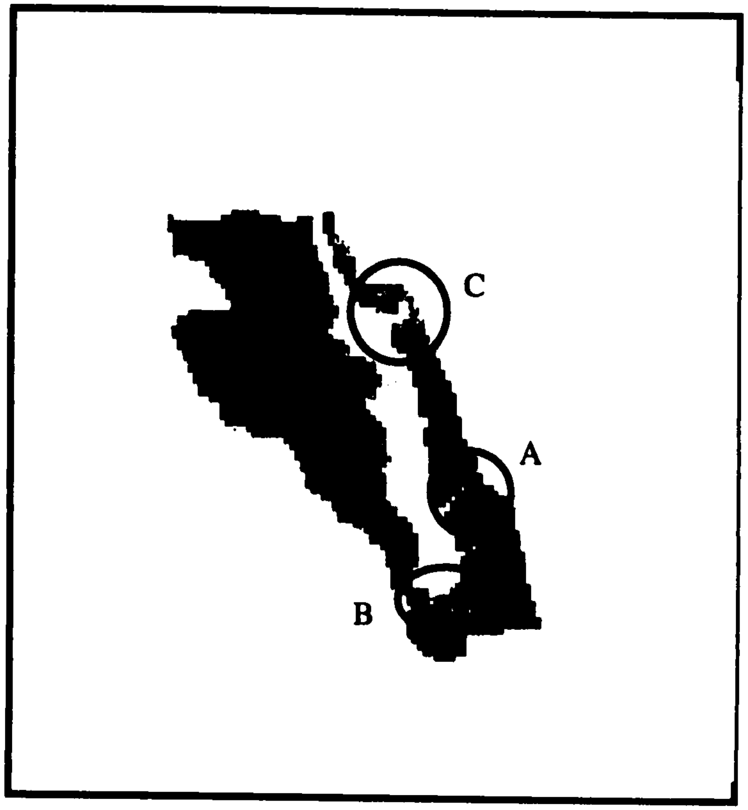
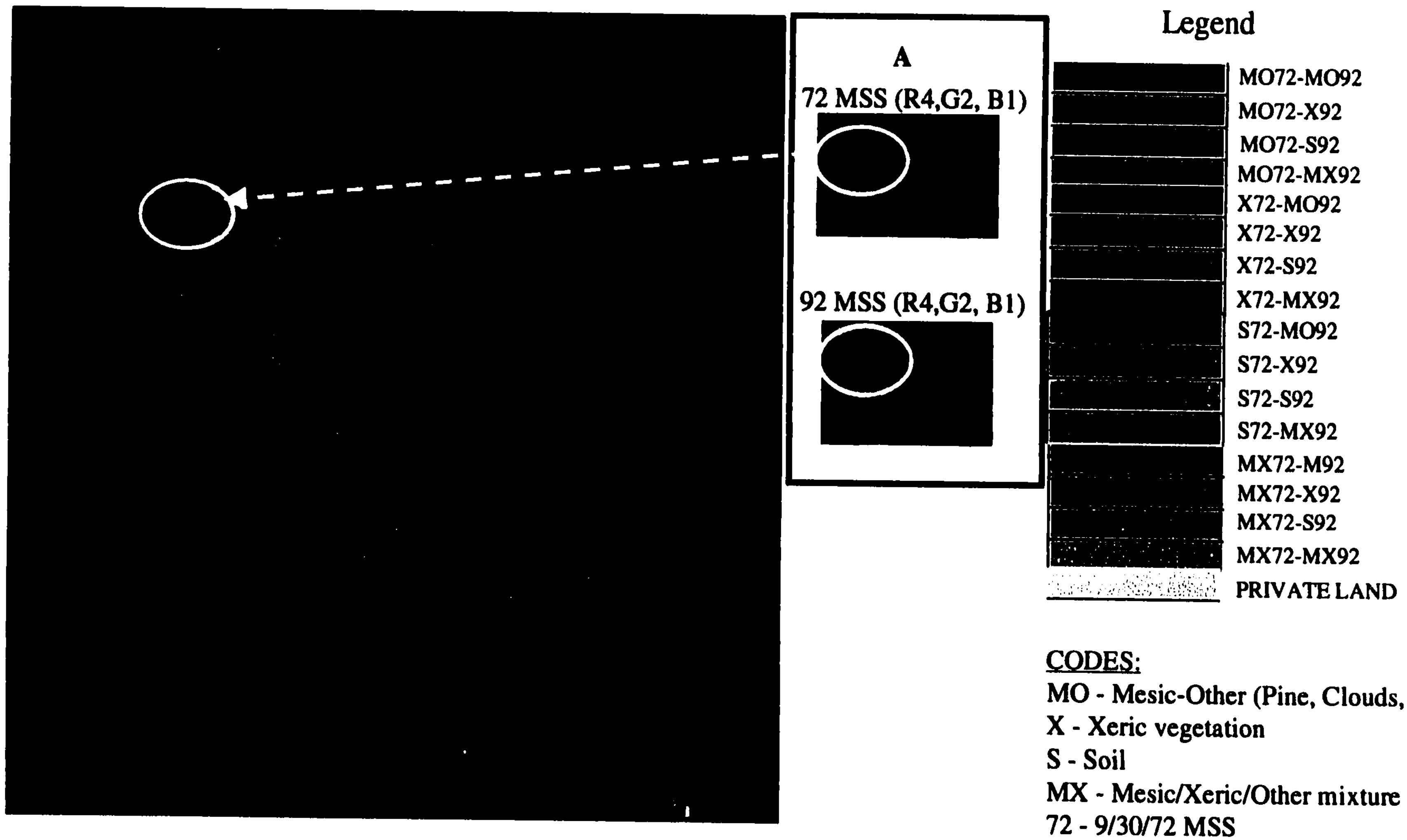


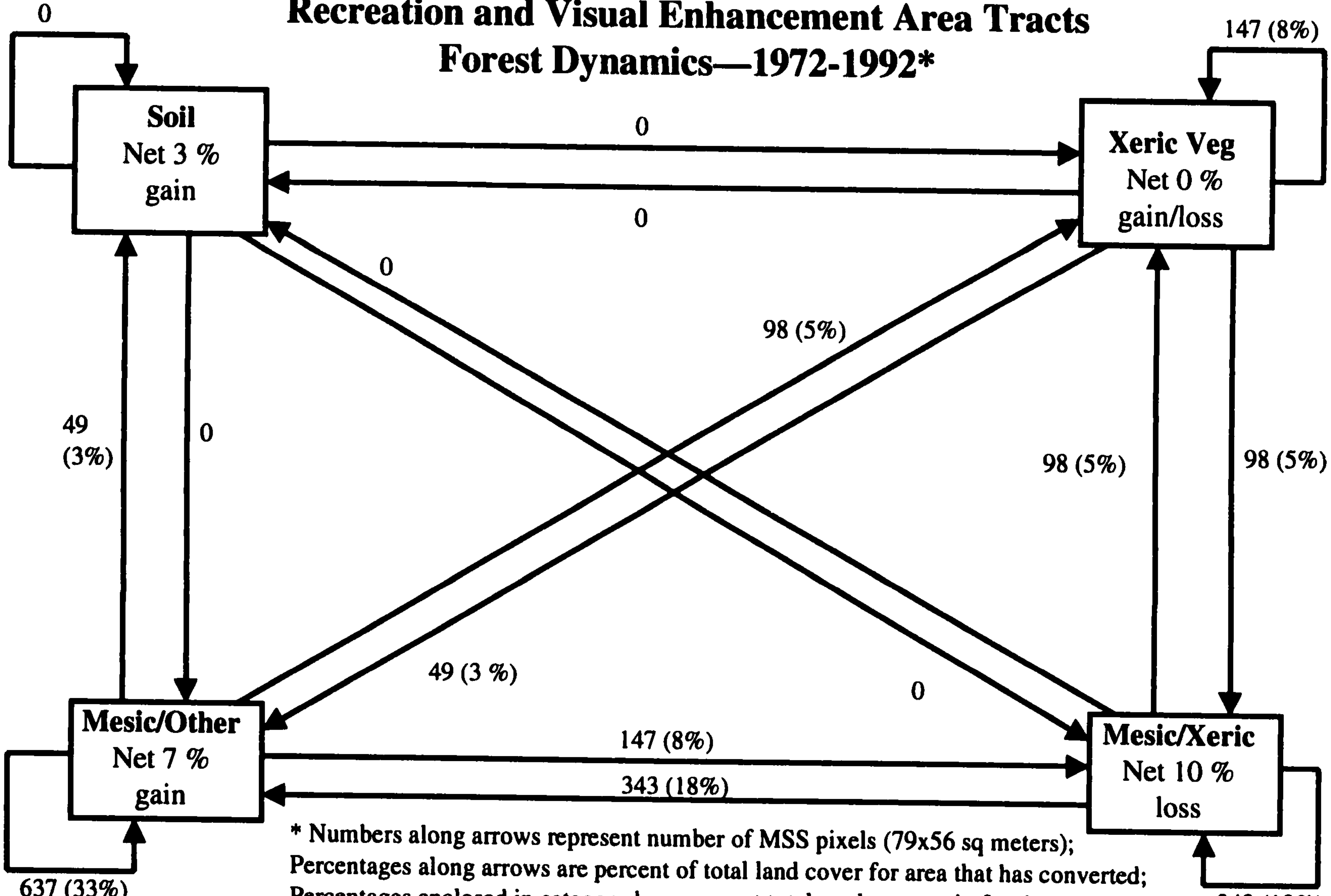
Figure 7-22: Yellowwood State Forest—Classification Change Map Recreation and Visual Enhancement Area Tracts*



<u>CODES:</u>
MO - Mesic-Other (Pine, Clouds, Shadow)
X - Xeric vegetation
S - Soil
MX - Mesic/Xeric/Other mixture
72 - 9/30/72 MSS
92 - 9/28/92 MSS

* Background 9/97 Landsat TM color composite (R3, G2, B1)

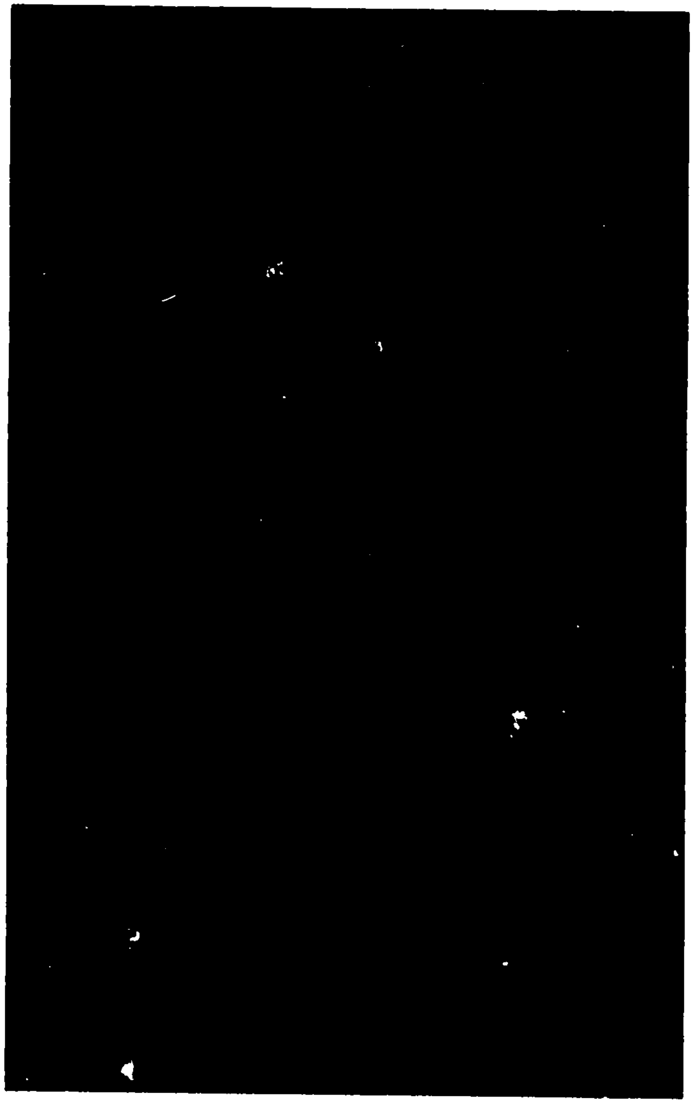
Figure 7-23: Yellowwood State Forest—Classification Change Map Recreation and Visual Enhancement Area Tracts Forest Dynamics—1972-1992*

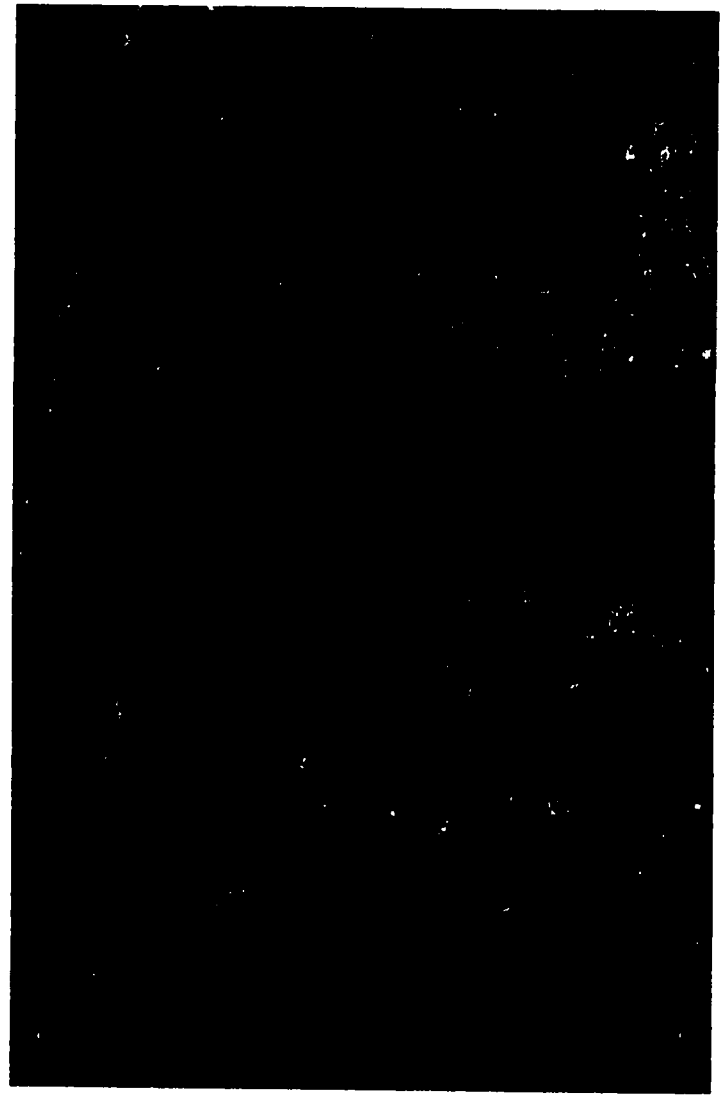


* Numbers along arrows represent number of MSS pixels (79x56 sq meters); Percentages along arrows are percent of total land cover for area that has converted; Percentages enclosed in category boxes report total net loss or gain for that category. Percentages may not total exactly because of rounding.

Figure 7-24: Yellowwood State Forest—Potential Commercial Timber Tracts Side by Side MSS Image Comparison (R4, G2, B1)

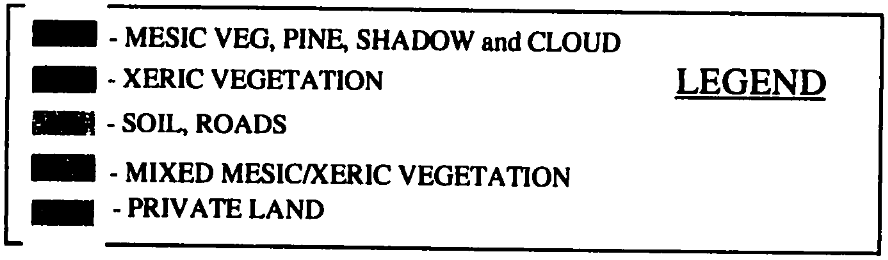
9/30/72 MSS
(R4, G2, B1)





9/28/92 MSS
(R4, G2, B1)

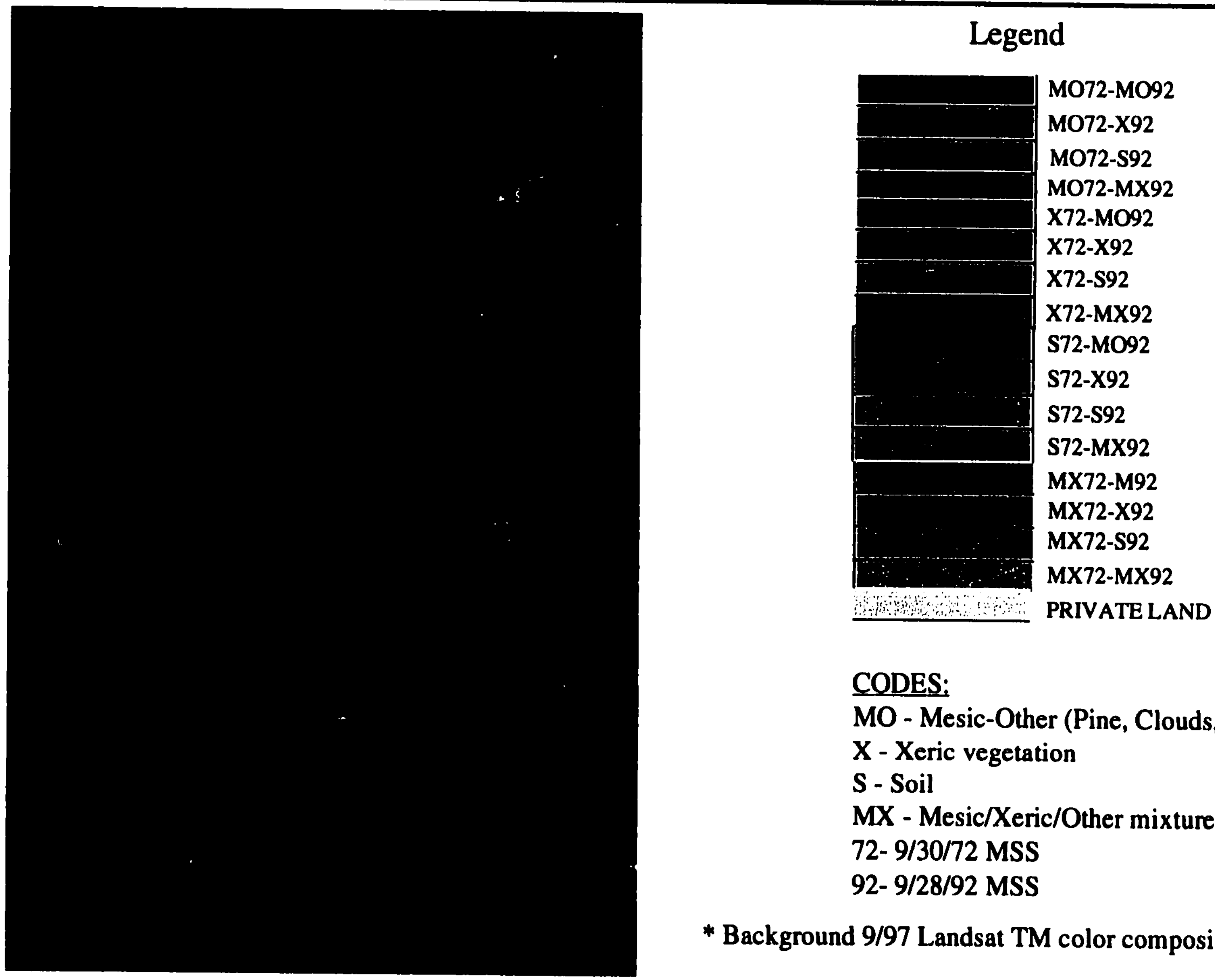
Figure 7-25: Change in the Yellowwood State Forest—Potential Commercial Timber Tracts



9/30/72 MSS SMA-BASED CLASSIFICATION

9/28/92 MSS SMA-BASED CLASSIFICATION

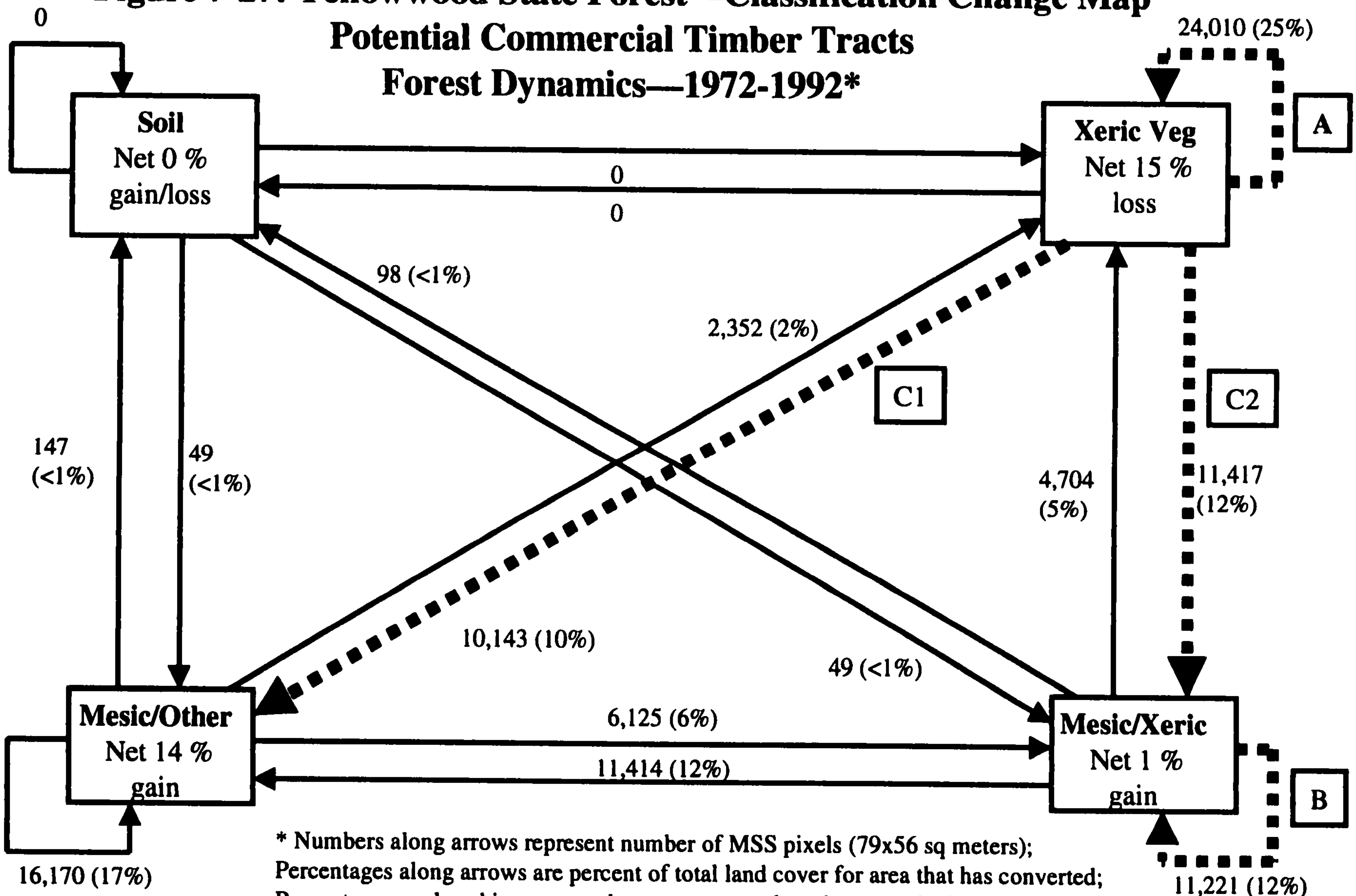
Figure 7-26: Yellowwood State Forest—Classification Change Map Potential Commercial Timber Tracts*



<u>CODES:</u>
MO - Mesic-Other (Pine, Clouds, Shadow)
X - Xeric vegetation
S - Soil
MX - Mesic/Xeric/Other mixture
72- 9/30/72 MSS
92- 9/28/92 MSS

* Background 9/97 Landsat TM color composite (R3, G2, B1)

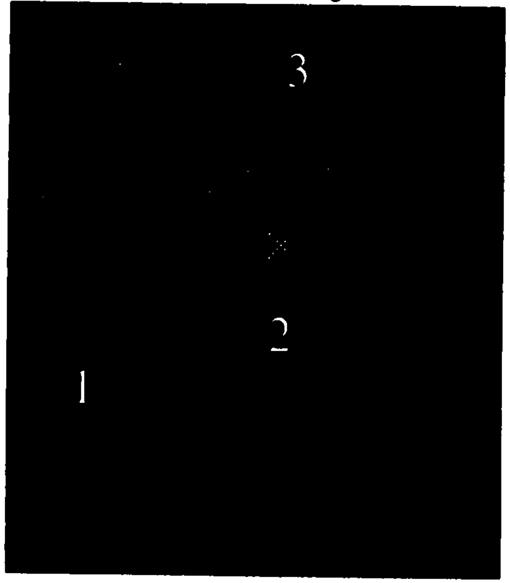
Figure 7-27: Yellowwood State Forest—Classification Change Map
Potential Commercial Timber Tracts
Forest Dynamics—1972-1992*



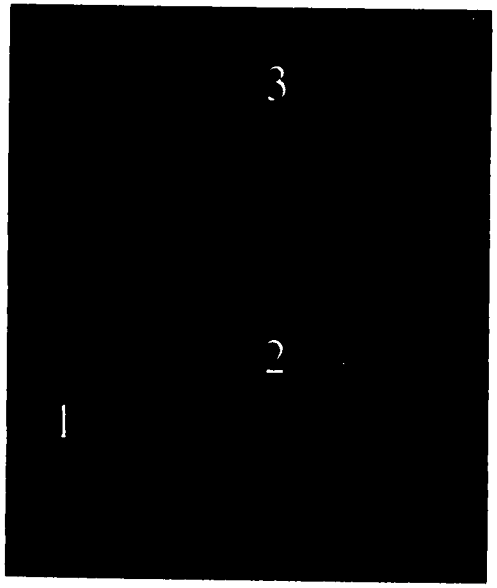
* Numbers along arrows represent number of MSS pixels (79x56 sq meters);
Percentages along arrows are percent of total land cover for area that has converted;
Percentages enclosed in category boxes report total net loss or gain for that category.
Percentages may not total exactly because of rounding.

Figure 7-28: An Example of Three Different Clearcut Locations in the Hoosier Pleasant Run Unit and How they Differ Spectrally

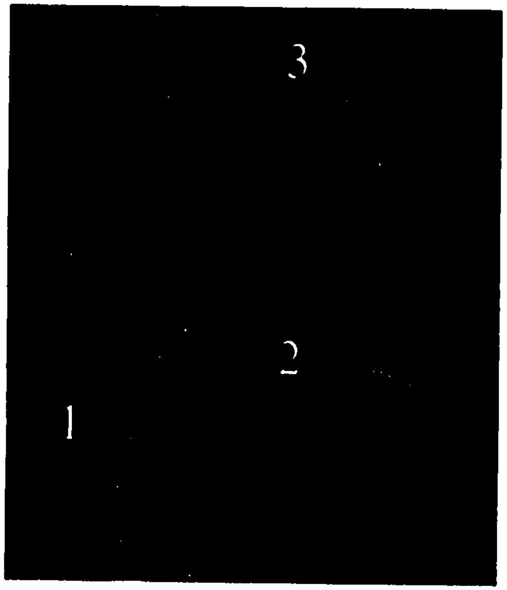
A. USGS 7.5' topographic map



B. 9/30/72 MSS (R4, G2, B1)



C. 9/01/85 MSS (R4, G2, B1)



D. 9/28/92 MSS (R4, G2, B1)

Chapter 8

CONCLUSIONS

"Human actions rather than natural forces are the source of most contemporary change in the states and flows of the biosphere" (Turner and Meyer, 1994 3)

If we accept the above statement by Turner and Meyer as true, then at the core of the Human Dimensions of Environmental Change research agenda is the puzzle of how to relate human actions to change in natural resources. There is the pressing need for research that separates the effects of natural forces from those of human action on natural resource conditions. This in and of itself is a complex research problem.

But the ultimate goal of this major research program is not just to link human actions to outcomes—it is more extensive than that. The ultimate goal is to inform policy-makers at all levels of governance about how existing (or proposed) incentive structures (in the form of legislation, standard operating procedures, social norms and customs, etc.) influence human decision-making and action and then also to relate actions to outcomes in natural resource condition. It is only by linking incentives to actions and actions to outcomes that we will be able to understand whether a particular policy or suite of policies produce intended results.

I have emphasized throughout this volume that the incentive structures people face as they make decisions related to natural resource use and management are fashioned through the particular configurations of physical, human community and institutional landscapes. By conceptualizing these as overlapping landscapes, I am emphasizing the point that each of these three components has geographic properties to them. Architects, biologists, ecologists, engineers, geographers, geologists and others all study the three dimensional physical world in great detail. Anthropologists, demographers, ethnographers, geographers, historians, political scientists and others all have interests in the geographic distribution of the human population residing in and around a particular physical landscape. For example, demographers and geographers have made great strides toward understanding how human communities are shaped and change as birth, death, in- and out-migration rates change in a geographic context.

But less attention has been given to the study of the third landscape, the institutional landscape, and how past and present geographic institutional configurations have altered the incentive structure humans face in their day-to-day lives. There are, however, some notable exceptions. Some political scientists are devoting efforts toward understanding the influence of voting district boundaries on election outcomes or where, geographically, government services are provided (e.g., Williams, 1995). Others have studied the impact of economic institutional boundaries, such as enterprise zones, on improving community landscape conditions (e.g., wages). Criminologists and policy analysts have studied how various policing or community association activities produce shifts in the location of crime "hot spots" within a physical landscape such as a city. But aside from a scattering of such studies, research on the spatiotemporal dimensions of institutions has been largely ignored. Few, if any, have attempted to understand how changes in the institutional patterns governing a natural resource influence geographic patterns in human behavior, the actions they take and ultimately the outcomes produced.

Chapter 1 argued that a primary reason we know so little about this topic is because of the "information and knowledge gaps" we possess. Let me reiterate them here

> *Information Gap 1: In a majority of circumstances, we lack baseline inventory data on the condition of the natural resource. In cases where such data exists, it is either not georeferenced, or it is georeferenced in some aggregate form*

> *Information Gap 2: In most circumstances, we lack longitudinal, georeferenced data on natural resource condition.*

> *Information Gap 3: In nearly all circumstances, we lack longitudinal, georeferenced data about the institutions that have governed the natural resource.*

This lack of information leads to gaps in our theoretical understanding:

> *Knowledge Gap 1: We possess an incomplete understanding of the longer term effects direct human action has on natural resource condition.*

> *Knowledge Gap 2: We lack knowledge on variables that act as indirect forces that lead to changes in natural resource landscapes.*

> *Knowledge Gap 3: We lack understanding about how changing scale influences our findings related to human action and natural resource landscapes.*

And finally, a more technical knowledge gap, but an important one nevertheless:

> *Knowledge Gap 4: We do not adequately understand the relationships between the information provided by satellite images and the land cover on the ground. Moreover, we do not have well worked out methods on how to apply them to study the human dimensions of environmental change.*

Recent technological and analytic advances provide opportunities for overcoming these information and knowledge gaps. With these advances we can investigate linkages between incentive structures, human decision-making, human actions and outcomes more thoroughly than we could have ever imagined ten or even five years earlier. The two parts of this dissertation take advantage of these technological advances and study two very different forest governance situations. Let me turn to a brief summary of findings, methodological advances and implications for policy and policy analysis for each of these studies. After that, I will summarize the broader implications of presenting the two studies side-by-side in one volume. I will conclude with a discussion of research opportunities that build upon the work reported in this dissertation.

Summary and Significance of Study I : Identifying Human Induced Change in Forest Resources in Situations Where No Baseline Condition Data Exist

Chapter 2 describes the situation commonly faced by researchers in many parts of world where no baseline data exists on the condition of a natural resource. The objective of the study, methodologically, was to develop techniques to extract additional information about human induced change from baseline forest inventory data collected in the field during the first and only visit to the site. This is a common situation facing researchers undertaking empirical environmental studies, especially in countries that have few available funds for inventorying their natural resources.

While methodological advances were an important objective of the study, a second objective was just as important. The study needed to address substantive, empirical questions that could inform forest policy in the region. A set of empirical questions were presented in Chapter 1. The research, conducted in the Kayar Khola watershed in East Chitwan Nepal, set out to determine how and where forests in the study area were changing, how human actions were contributing to these changes, and what system of incentives were in place that encouraged the actions taken. An emphasis was placed on collecting accurate, georeferenced information about the condition of the physical resource, along with the structure and composition of the community and institutional landscapes.

Substantive Findings and Implications for Policy

Villagers in this watershed rely on a multitude of forest products to support their daily livelihood. The most important forest product species, *Shorea robusta*, was chosen for study. It is assumed that if patterns of human disturbance in the forests will appear, they will be manifested first in the distribution of species the community relies on the most. Theory suggests that one of three possible spatial distributions will be identified. First, there is the pattern predicted by forest ecology theory: if the villagers harvest *Shorea robusta* in quantities that are easily replaced by natural forest regeneration, the spatial distribution of *Shorea robusta* should follow its natural clumped distribution over geographic space. Second, there is the pattern predicted by optimal foraging theory: if forest protection rules are ineffective and the forest is open access, optimal foraging would predict that *Shorea robusta* depletion will be the greatest in areas nearby and easily accessible to human settlements. Third, there is the pattern predicted by what I label the "optimal foraging under institutional constraints" theory. This theory predicts that patterns in vegetation depletion will follow optimal foraging patterns except when nearby or easily accessed areas fall under effectively enforced protection rules. This third theory predicts a vegetated landscape reflecting patterns of effectively enforced institutions.

It is here that I ran into Information Gap 1. No baseline forest inventory data has ever been taken in this area. Consequently, I turned to a geographic analysis to assess patterns of human induced change using inventory data collected during our site visit. Locations of sampled forest plots were carefully recorded using differential global positioning system (DGPS) technology The spatial analysis of these plots reveals that geographic patterns of *Shorea robusta* support the "optimal foraging under institutional constraints" theory After controlling for natural effects such as topography, soil, competing species, etc., depletion of *Shorea robusta* is still higher in the eastern forest The combination of social structures between villages (a component of the community landscape) coupled with stronger forest monitoring mechanisms in the west (an attribute of the institutional landscape) result in higher levels of foraging in eastern forest locations

Implications of this study for forest policy in the region? These findings suggest that past and present configurations of the physical world and community landscape coupled with the institutional landscape have produced unintended consequences–a shift of human foraging farther back and to the eastern side of this watershed. Certainly, this shift is not what Division of Forestry (DFO) officials intended when they established the rules and monitoring mechanisms to govern these forests The findings suggest that either: (1) more roads need to be built in inaccessible areas to make monitoring more effective; (2) more guards need to be hired to monitor the pressured areas; or (3) some alternative institutional landscape needs to be developed Given topographic and fiscal realities, the first two options are really not feasible. This study recommends the third option where more control is provided to the community members themselves to devise their own rules and monitoring mechanisms related to these forest resources. In this case the DFO would be better off providing assistance toward the development of villager associations and effective conflict resolution mechanisms.

Methodological Contributions

This study devises a way to get around Information Gap 1. In my opinion, this problem of no resource inventory is perhaps the greatest problem facing the human dimensions of environmental change research community and natural resource policy-makers and analysts undertaking empirical studies. Without data on natural resource condition, it is impossible to say anything about how human actions have modified the physical landscape because we have no idea of the natural distribution of vegetation prior to human settlement.

But this study provides an example of how the "no forest inventory" problem can be overcome by building on what geographers and anthropologists have long understood: that human actions leave imprints in the physical landscape. This study provides an example of how we can collect well georeferenced field data of a natural resource and analyze it for human- produced patterns. DGPS technology--something that is becoming cheaper and more readily available to researchers every day--coupled with plot measurements of forests, including ones within a relatively undisturbed reference forest, and GIS and spatial statistics provide researchers with mechanisms for controlling for natural effects and identifying patterns in vegetation that are in response to human activities. Analytically, this study provides one example of how geographic relationships might be analyzed by applying a trend surface regression model. But there are other spatial statistical techniques (e.g., tests for spatial autocorrelation, krieging, landscape ecology metrics, etc.) that might be utilized to answer questions related to human-environment relationships. This study shows that the extra effort in the field required to gather well georeferenced data about the physical natural resource while collecting other information on past and present community and institutional configurations can go a long way toward closing the information gaps listed above. Its substantive findings contribute, to the extent one case study can, to filling in the first three knowledge gaps as well.

Summary and Significance of Study II : Capitalizing on Multispectral Satellite Time Series Data to Understand the Human Dimensions of Environmental Change

The second study in this dissertation–Chapters 3 through 7–provided an alternative approach toward solving the information gaps outlined above. Over the last quarter of a century, NASA's Landsat program has amassed a significant time series of multispectral images for nearly every land location on Earth. The objective of this part of the dissertation was to develop methods to link human incentives to actions and actions to outcomes in a forest environment using a time series of Landsat multispectral sensor (MSS) satellite images to measure changing forest condition.

But here, too, the development of methods was not the sole objective of this study. The same set of empirical questions addressed in Study I were repeated here but the emphasis shifted to a very different physical, community and institutional environment: public forests in south-central Indiana, U.S.A. This study set out to answer this substantive research question: Do two public forests, Yellowwood State Forest and Hoosier National Forest, both possessing similar physical landscape features (the Brown County hills) and community landscape histories but different institutional histories, exhibit substantially different forest conditions (outcomes) after twenty years?

Substantive Findings and Implications for Policy

Several steps were required to answer this question. The first step, described in Chapter 4, developed the theoretical framework for study and provided a history of the institutional landscapes and the incentive structures guiding forest property manager's day to day decision-making and operational-level activities in these two public forests. From this effort, it is clear that although both the State Forest and the National Forest were managed for multiple uses–including timber production–over the life span of the Landsat MSS system (1972-1992), significant modifications made in the 1980s to the institutional landscape of Hoosier sharply curtailed cutting activities. Moreover, modifications in the internal institutional landscape of the Hoosier, such as the 1982 designation of the Deam Wilderness Area, led to some areas being more protected from cutting or other significant human disturbance activities than others. The findings in Chapter 4 led to the development of testable hypotheses about forest change over the twenty year period for different management units within these two public forests.

The second step of this study, undertaken in Chapters 5 and 6, worked to determine whether the spectral, spatial, radiometric and temporal resolution of a three time point Landsat MSS time series was sensitive enough to capture human disturbances in the deciduous forest canopies in south-central Indiana. Chapter 6 conducted image processing steps to ensure that images taken in different years by different satellite platforms were comparable. Once it was clear they were, the rest of the chapter investigated the sensitivity of these images to typical activities conducted by public property managers in these forests using well-documented maps of known activity locations in another state forest–Morgan-Monroe–used as a reference forest. The findings from Chapter 6 prove, fairly convincingly, that the time series of MSS images are sensitive to many human-induced forest disturbance activities in the region, including new development and cutting activities. Chapter 6 also discovered that areas subject to cutting emit a more xeric-looking (brighter) reflectance spectra in the near-infrared bands of MSS whereas older forests emit a more mesic-looking (darker) spectra. Of course, the larger the area disturbed and the closer in time the action occurred in relation to the next satellite image in the time series, the more likely the action will be identified in the MSS sequence.

Chapters 5 and 6 contributed in another way. They applied a relatively new image processing technique called "Spectral Mixture Analysis" (SMA) to the study of human activities in deciduous forests. While spectral mixture has been applied by researchers studying the geologic formation of the Earth or other planets, only a few researchers have tried to apply it to the study of the human dimensions of environmental change (e.g., see Adams *et al.*, 1995). The image processing tasks and SMA conducted in Chapter 6 are important analytic steps, for together they allow us to develop measures of land cover that are based on fully processed images calibrated to at-surface reflectance rather than analyzing directly the "raw" 8-bit at-satellite digital numbers (DN) that are sent by EROS data center or EOSAT (the two primary U.S. repositories for Landsat images). Analysis of DNs are the more common technique in human dimensions of environmental change studies to date (Green, Schweik and Hanson, 1998). Fully calibrated images have the advantage over 8-bit DN representation in that they can be directly compared with calibrated images from other locations because they represent a physical measure of land cover: light reflectance. This canot be done with images with data still in DN format (Ibid.). The added processing in Chapter 6–radiometric calibration, atmospheric correction and radiometric rectification–allowed the creation of a land cover classification in Chapter 7 that can be applied anywhere in the world where it is deemed appropriate.[1]

Taking advantage of the fully processed MSS image products, Chapter 7 then tested the hypotheses presented in Chapter 4 regarding forest change under different institutional histories. This chapter presented the surprising finding that, regardless of institutional history, forest canopies of these two public forests in 1992 have generally exhibit a more mesic spectral reflectance when compared to the images taken twenty years earlier. *If* the mesic/xeric spectra distinction can be used as a proxy for age class–and the findings in Chapter 6 suggest that it can (see also Green, 1988, 1996)–then it appears that the public forests in Indiana are, in general, getting older. This suggests that, in the context of these state and national forests, the rules related to maximum allowable cuts, the multiple use mandates, and the silviculture methods[2] used are achieving what they intended: they are allowing the majority of the public forest land to mature over time.

The study also found, as expected, that certain areas designated as high intensity recreation had higher degrees of soil exposure–evidence of development–than areas not falling under these designations. Similarly, areas subject to higher levels of preservation, such as the Deam Wilderness, exhibit signs of forest regeneration in areas within their borders that in 1972 exhibited exposed soil. The forests in these regions appear to be regenerating.

Finally, the hypothesis proposing that legislation-based incentive structures encourage State Forest property managers to undertake a higher level of timber production activities than their National Forest counterparts was tentatively confirmed. Forest dynamics summaries for Yellowwood and Hoosier based on MSS produced forest change classification maps reveal a higher degree of spectral trajectories in Yellowwood property that, based on findings in Chapter 6, are associated with timber cutting activities (see for example, Figure 7-27)

What is the implication of this study for forest policy in the region? The debates over appropriate management of public forests in the United States and the services State versus National Forests should supply are never ending. The fact that all of the forest management units studied, regardless of the state or national distinction, reveal signs of maturing vegetation lends support to both state and national forest officials' statements that they are committed to maintaining a mature forested landscape. From a multispectral satellite view, using mesic/xeric as a proxy for age class, it does show that the forests overall are getting older.

The analysis also shows that forest property managers do respond to the incentive structures placed on them by state or national legislation. The legislation adopted during the 1980s at the national level has significantly raised the cost of timber production activities in national forests. The analysis of forest change in the Hoosier reveals few areas that appear harvested in recent years. Alternatively, state legislation in Indiana has established a revenue allocation scheme encouraging timber production in state forests. The forest dynamics summary for Yellowwood exhibits a higher level of spectral cutting trajectories than found in Hoosier locations. Whether state versus national forest land should be used to provide timber is a hotly debated subject, but differences in their management are expected. The findings here are consistent with a Federalist system of government. I conclude from this analysis, however, that citizens who lash out at public property managers or other Division of Forest bureaucrats over timber harvesting activities are addressing the wrong audience They should be arguing with state and national legislators who maintain the system of incentives that these property managers and officials base their decision-making and actions upon.

Finally, I should note that there are some limitations to this second study's findings. First, Chapter 7 describes fully the problems that lighting geometry causes in the identification of cutting locations over a broad landscape. Cuts residing on south, southwest, southeast and eastern slopes will be more illuminated in south-central Indiana. This is because the sun is always in the southeastern sky when Landsat images are taken. Cuts falling on southwest, west, northwest and north-facing slopes make identification of xeric areas more difficult because of the shadow effects from taller, adjacent stands left untouched For this reason, I consider the findings in regard to cutting for Hoosier and Yellowwood tentative There may be more cutting in both of these forests that I did not successfully identify because of the shadow Additional systematic analysis of known cutting areas across all topographic gradients are required to get a better handle on spectral trajectories of these activities Second, this study provides a comparison of cases: one state forest and one national forest Because this is a case study, the findings here should not be taken as generalizations of behavior for state and national property managers in all public forests.

Methodological Contributions

While the substantive findings in the second study are useful in and of themselves, the real strength of this part of the dissertation is in the methods it has developed. I began work on this second study just as the Center for the Study of Institutions, Population and

Environmental Change (CIPEC) was created at Indiana University. CIPEC's charter is, in part, to develop an interdisciplinary suite of methods for the study of human dimensions of environmental change. Methods used by scholars in the fields of anthropology, demography, forest ecology, political science, geography and remote sensing are to be applied together. My own personal quest, at the encouragement of Elinor Ostrom, J.C. Randolph, Emilio Moran, Glen Green, Rosemary O'Leary, John Williams and others, was to begin to devise methods for linking institutional analysis used by political scientists to Geographic Information Systems and multispectral satellite images—a task no one else, to my knowledge, has ever attempted.

It became clear to all of us at CIPEC at the outset that given the technical nature of GIS and remote sensing, the only way to build a significant research program that yields consistent results across study sites was to develop and document methods. During every step of the analysis described in Chapter 6 and 7 of this study, I hit technical and analytic challenges with no real cookbook of techniques to follow at my disposal. Given that many other colleagues working at CIPEC or who attend CIPEC's Summer Institute are trying to do similar things at other locations in the Western Hemisphere, I though it important to fully document the steps I took so others, facing similar analytic problems, had less of a learning curve. The documents I have written are nearly a dissertation in and of themselves. With this introduction, I will now list some of the major methodological contributions this study has made to advance the Human Dimensions of Environmental Change research program.

Developed Procedures for the Radiometric Calibration, Atmospheric Correction and Radiometric Rectification of MSS Images

Without converting the raw DNs of the MSS images provided by the satellite system to at-surface reflectance, none of the later analysis (e.g., spectral mixture, classification based on spectral mixture) could have been accomplished. However, figuring out this conversion was by no means an easy task. There is a literature available describing how to undertake these data manipulations, but it is difficult to locate (papers are not always available in standard peer- reviewed journals) and not readily accessible to a researcher who lacks a Ph.D. in remote sensing. With assistance from Glen Green, CIPEC's remote sensing post-doctoral fellow, I developed a spreadsheet that conducts the relatively complex mathematical computations required to convert the at-satellite digital numbers (the format these images arrive in when they are ordered from EROS or EOSAT) to at-surface reflectance (Appendix D). I also developed a methodology based on Hall et al. (1991) to normalize or radiometrically rectify one image to another to ensure comparability (see Appendix C).

I don't think I can overemphasize the importance of these procedures. The spreadsheet is capable of processing *any* MSS image regardless of whether a header is or is not included in the shipment. This means that MSS data from other image repositories other than EROS data center, such as the North American Landscape Characterization program, which supply *free* Landsat MSS "triplicates" for the *entire* U.S. and most of Mexico but in DN format and without header information, can be fully processed to at-surface reflectance. Once these images are converted they can be compared with any other image of another location. The ability to compare landscape change side-by-side is absolutely critical if the environmental change research community is to move beyond individual case studies to more comparative research. It also creates opportunities to take multiple neighboring images and scale up from relatively fine spatial scale study sites to broader geographic regions as part of the global change research agenda. This moves us farther toward addressing Knowledge Gap 3 (the problem of scale). At CIPEC, the MSS processing techniques I developed above are already being applied to other research projects in Brazil, Mexico and shortly on images from Nepal

Several other procedures were developed and documented that will be helpful for other researchers affiliated with the CIPEC research center. For instance, I developed a method to greatly reduce the amount of shadowing that appears in an image with hilly terrain based on a digital elevation model (Appendix E). I also developed an approach to create a "hillslope profile" image a GIS coverage based on a DEM that identifies pixels falling under particular topographic domains (e.g., summits, valleys, slopes). The hillslope profile image for this study helped me to validate what kind of topographic conditions particular pixels fell in Chapter 6. I am hopeful that this documentation will be used by researchers undertaking other CIPEC research projects, especially ones investigating hilly terrain areas

Initiated a Spectral Library of Endmembers for Midwestern Deciduous Forests

The endmember spectral library presented in Chapter 6, Figure 6-13 and Table 6-1 is particularly exciting because it initiates a collection of known spectra for pure areas within the Indiana landscape. This moves us beyond what is typically done in land cover studies that have utilized satellite images. I have stated that often satellite images are processed using their original DNs rather than taking the effort to convert them to at-surface reflectance. In many research situations this may be perfectly appropriate (see Green, Schweik and Hanson, 1998). For example, in cases where the researcher is conducting a one-time point, one location study with no intention to do comparative work in the future, no conversion is required. But it is impossible in these instances for other researchers to build on the study because the DNs are scene dependent. They have atmospheric and sensor effects in them (refer back to Figure 5-5). By applying the procedures we have developed above, the images in this study represent the percentage of light reflected by the surface land cover along different locations of the electromagnetic spectrum. Recall Figure 6-13, which provides a graphical representation of the reflectance properties of three "spectrally pure" endmember locations. By publishing these spectra, any researcher can do a comparable analysis of an image by applying these endmembers for their Spectral Mixture Analysis. This technique allows us to conduct image analyses that are directly comparable across multiple locations.

In addition, the SMA analysis has initiated a "spectral trajectory library." By publishing the spectral properties of areas that have been subjected to human activities as I have done in Chapter 6, we begin to record how known human activities alter forest reflectance spectra over time. Further research is needed to develop a larger sample of known human disturbance trajectories.[3] Eventually, it may be possible to identify relationships between forest vegetation reflectance and other physical parameters such as stem biomass or perhaps even carbon content. If a relationship can be identified between spectral values or SMA fractions and these other forest measures, it may be possible to create landscape-level map inventories of important global change parameters such as amount of carbon sequestered (Green, Randolph and Ostrom, 1998). These maps could then be used as inputs to other research, such as global climate models. These libraries help to close Knowledge Gap 4

Developed an Initial Forest Classification System That Can Be Applied to Other Locations

Because I converted the MSS images to at-surface reflectance and created the SMA endmember fraction images, I was then able to develop an image-based forest classification system for the deciduous forests of south-central Indiana. The importance of this classification is that it can be replicated by researchers in other locations with comparable forest types. Recall that traditional image classification is usually applied using DN images that are scene-dependent. Classes are created statistically from the DNs themselves. SMA-based classification allows the analyst to specify classes based on a physical measure -light reflectance- and classes can be defined based on these physical properties and not on statistical clusters that vary from image to image. For example, in this analysis, I defined a "xeric vegetation dominated forest" as one with greater than forty percent xeric reflectance, and less than forty percent mesic vegetation and soil reflectance. This definition of a forest can be easily replicated by researchers studying other locations.

By moving toward classifications based on physical reflectance, we are devising a classification system that is grounded on physical measurements of light (in this case "mesic" and "xeric" vegetation reflectance). More traditional classifications often confuse land cover with land uses. For example, analysts may label a computer-generated class of digital numbers as "pasture." But what exactly is a pasture? It is a human-produced *label* we give to a field used for animal grazing. The term pasture has no direct link to physical light reflectance. Two pastures at two different locations may have very different light reflectance properties, depending on the amount of soil exposed and the type of vegetation within its borders. By following the SMA classification technique undertaken here we move toward the use of a true measurement of land cover light reflectance. The job of the analyst is to clearly define land cover types by their reflectance properties as I have done in Chapter 7, Table 7-2.[4] This dissertation makes an important contribution by providing an example of how this is done and then linking a reflectance-based classification to human actions and incentives.

Linked Institutional Analysis and Remote Sensing

Finally, great strides have been made in individual disciplines such as political science, geography, remote sensing, forest ecology, policy analysis and others addressing components of the human-environment relationship. We are all aware, however, that the problems humanity faces related to global change do not fall nicely along disciplinary lines. In order to get our arms around human-environment issues we need to develop bridges across disciplines and link disciplinary approaches. There is a practical side as well: research funding sources have reached this same conclusion and are encouraging multidisciplinary endeavors.

At the outset, one of the primary objectives of this dissertation was to link approaches to the study of institutions developed by political scientists to tools and techniques used by geographers and scientists of remote sensing. The integration of these techniques becomes readily apparent in both studies but especially in Chapters 4 and 7 where the changing institutional landscape of the Hoosier National Forest is analyzed. This dissertation demonstrates that by applying GIS tools, it is possible to link theoretically based predictions of human behavior based on incentive structures to change that is captured by multispectral satellite images. This moves us a little further in closing Knowledge Gap 3: the scaling problem.

Significance of the Research and Broader Implications

Some readers skimming through the volume and this chapter will wonder: Why are these two studies important? What contribution do they make? Why are they together in one volume?

It should be apparent that each of the two studies stands solidly on its own: they both analyze a particular forest governance setting, apply appropriate theory to the situation, and provide substantive findings helpful to local policy-makers. They each individually address both the empirical and methodological questions stated in Chapter 1 and the information and knowledge gaps specified above. It is hoped that the individual discussions about them in this chapter have answered many of the questions as to why each of the two studies are important and how they contribute to broader knowledge. Next I will address the third question: Why together in one volume?

The two studies, placed side by side, provide methods to overcome *all* of the information gaps outlined above and in Chapter 1. To understand human induced *change* in a natural resource, we either can study the patterns in forest condition from one time point as was done in the case from Nepal, or we can capitalize on remote sensing data sets that have amassed multiple time point data for nearly every land mass on the Earth.

Because temporal sets of Landsat Multispectral Scanner and Thematic Mapper images have been taken for most of the world's land resources over the last twenty-five years, it makes sense to take advantage of these important environmental change data resources The Indiana study provides an example of a careful, systematic approach to using these datasets and how they can be applied to the study of human created institutional landscapes and incentive structures. In short, the studies together show that regardless of how limited information is on the condition of a physical resource in any location in the world, there are ways to understand the human dimensions of change in that resource.

Further, the two studies together demonstrate convincingly that humans respond to their incentive structures and these incentive structures have spatiotemporal properties. Each study shows that the geographic configuration of well enforced rules can dramatically alter human behavior and, over a series of years, can lead to significant changes in the look of the forest. In the Nepal study, the enforcement of rules in the western part of the region produces a shift in the foraging behavior of humans toward the east. In the Indiana study, well-defined property rights structures in the U.S., variations in rules related to collective-choice mechanisms (e.g., degrees of public participation in property level planning) between state and national forest organizations and the subsequent incentive structures that drive property planning and management have produced differences in the types of activities permitted in certain forested areas and reveal differences in canopy reflectance. The Indiana study, particularly the Hoosier component, provides a great example of how the institutional landscape of a location may change over time, just as communities and physical landscapes change. If we are concerned about the longevity of natural resources, we must place a greater emphasis on establishing techniques to monitor the long term influence of stable or changing institutional landscapes just as we try and monitor how the physical world and communities change (e g . censuses). As this study shows, GIS technologies make this task slightly easier

Opportunities for Future Research

Upon completion of a project of this scope, it is important to consider future research opportunities that might build upon this work The theoretical and analytic approaches I have utilized in these study opens up a number of potential areas of endeavor Several have already been initiated. Let me first describe endeavors related to U.S. based studies and then close with discussions on future Nepal research. I hope to either conduct these projects myself or in conjunction with other colleagues affiliated with CIPEC.

Conduct a More Extensive SMA Classification of Indiana Forests Using TM Data

One difficulty in the Indiana study was conducting SMA on four band MSS images Even when landcover types (e.g., water) are clipped out of the scene prior to analysis, it is difficult to identify three endmembers that explain all the variation in pixels across the remaining landscape reasonably well Although the SMA processing conducted here does move us forward in developing classifications that are based on the physical property of reflectance and are replicable by other researchers, we still can do better. Recall that Landsat TM has six bands[5] of spectral information as opposed to MSS' four bands. By applying the same techniques–radiometric calibration, atmospheric correction, radiometric rectification, topographic normalization and spectral mixture analysis–on Landsat TM images, we can develop fraction coverages for five different endmembers: (1) xeric vegetation, (2) mesic vegetation, (3) soil, (4) pine and (5) shadow

The added two endmembers TM provides will allow us to model areas that had particularly high RMS error (lack of a good fit) in this study For example, the significant number of pine stands planted in the 1930s by the CCC in Indiana look very different spectrally and were not modeled well. More importantly, an SMA application with TM data will allow us to account for the shadow that is not removed by topographic normalization and hinders identification of forest cut areas under certain topographic regimes The improved spatial and spectral resolution Landsat TM images provide have the potential to overcome these difficulties If the shadow part of cutting can be better accounted for with a TM-based SMA approach, it should be possible to develop an age class based classification system for deciduous forests in the midwest United States based on mesic and xeric spectral properties. Such a classification would be a powerful tool for forest change monitoring in Indiana and elsewhere

Apply These Analytic Techniques to the Study of Private Forests in Indiana or Elsewhere

This work has concentrated on forest change under public property regimes in south-central Indiana. This is important, given that most of Indiana's public forest land exists in this area of the state. However, the majority of forested land in Indiana and across the U.S. fall under private ownership. Taking techniques developed here and applying them to answer questions about how and why private land owners are changing their forested land is a natural extension of this research.

From a policy perspective, there are good reasons to undertake such a research program. In Monroe County, Indiana, for example, a significant number of private owners live within the watershed of Lake Monroe: a lake which provides the water supply for the region. Understanding how private forest land is changing and why it is changing can help state and local governments design policy initiatives that protect water resources. Private forests–especially large areas–provide important habitat for Indiana's flora and fauna. And from a global change perspective, reforestation in Indiana helps reduce the amount of carbon in the atmosphere.

But little is really known about how forests are changing in private lands in this region. Two separate discussions I have had with policy-makers and county officials in the region lead me to this conclusion. The first discussion occurred when I recently visited a county planning office and made a presentation on some of my remote sensing work. In the discussion that followed it became apparent that aside from the rare circumstances where a time series of large-scale aerial photographs are used to answer a specific question, little information about land cover change over a broader temporal scale is used in planning initiatives. Planners told me that it is not so much that they don't want to use such information, it is more that they have not had temporal sets of satellite images available for use and they don't know exactly how they might use them effectively. But clearly, local and regional planning should involve a longer term vision and an understanding of trends that have occurred in the past and how these trends relate to institutional boundary configurations, such as zoning. The second discussion occurred over several meetings with Indiana's State Forester, Burnell Fischer, where he described two Indiana initiatives: the Forest Legacy program and the Heritage Trust program. In both cases, the Indiana

Department of Natural Resources Division of Forestry is trying to identify ecologically important or special forest land and encourage private owners to keep it intact. In the case of Forest Legacy, development rights are purchased from the owner. In the case of the Heritage Trust program, Indiana actually buys forest land threatened by development. The problem facing Indiana's Division of Forestry is how to determine where these threatened lands are located. There is a significant knowledge possessed by officials in the field, but GIS and remote sensing change maps and other analyses can surely help policy-makers as they work to spend precious funds wisely.

The discussions with these public officials made it obvious to me that the GIS and remote sensing products such as the ones created here can assist officials making policy and planning decisions. We need to answer policy-related questions: Where are forests being depleted in south-central Indiana? What factors contribute to their loss or where forests are returning? Where is the "development fringe" in the Indiana context and how is it affecting forest fragmentation? What are the important areas that need protection? What state programs appear to encourage long-term forest growth? What programs appear to be ineffective?

My colleagues and I at CIPEC have begun a major study of private forest owners in Monroe County, Indiana–part of the five-county region studied here. We hope to have interviewed 200 property owners about land use practices over the 1972-1998 time period by the end of the summer, 1998. The MSS time series and SMA classification techniques developed here will be applied to the Monroe County region with the hope that these products can help to answer some of these pressing questions. The human action spectral trajectories I have identified in Chapter 6 will help us interpret land cover change in the

200 or so properties we will have visited in the field. Multi-temporal classification maps will help us analyze the forested landscape across the entire county regardless of property regime to understand how it has changed. By spring of 1999, we hope to have some of the policy-related questions listed above more fully answered. In addition, I have an opportunity to pursue similar research in the context of Massachusetts or Connecticut, states with different settlement histories and different laws related to timber harvest practices on private lands.

Apply These Methods to a Study of Irrigation Management in Nepal

What should be apparent to the reader is that the methods developed here have more utility than simply forestry applications. For example, the spatial analysis of point data conducted in Chapter 2 is not limited to forest plots. During my last trip to Nepal, scholars at the Institute for Agriculture and Animal Sciences at Rampur, Chitwan and I applied differential GPS and collected the locations of over 45 farmer managed irrigation system headworks.[7] These systems provide a fascinating natural experiment, for they reside along seven seasonal river systems all parallel to one another and each flowing north to south. My colleagues have collected a tremendous amount of information for each of these systems related to how farmers collectively manage their irrigation systems. We have information pertaining to water allocation schemes, how rules for maintaining the systems are devised, what problems they have encountered, system performance, etc.

The DGPS headwork data provides accurate (±5 meters) measurements of where these systems meet their water source. We can begin understanding how geographic relationships encourage or discourage farmers to work together and collectively manage and maintain their systems. We would expect, for example, that the institutional configurations found in these systems will be correlated with their position along a river. Irrigation systems with intake points farther north have first access to water, and therefore may not require as stringent water allocation rules because the water supply is relatively abundant. However, irrigation systems with intakes farther south along the same river may have water scarcity problems. There may be very stringent water allocation rules under these circumstances and conflicts between appropriators may be more prevalent. Further, there are interesting geographic problems/issues across irrigation user communities. For instance, my colleagues in Nepal have identified cases where farmers living in upstream and downstream communities using different irrigation systems have had some serious conflicts over first rights to water. On a more positive note, there may be patterns where innovative institutional solutions are shared between neighboring communities of farmers. I expect the first law of geography to be apparent in the irrigation institutional landscape of this region: the institutional configuration of neighboring irrigation systems will be more alike than irrigation systems far apart.

By linking the institutional data to a GIS of irrigation headwork points, I can start investigating how geographic relationships affect the way rules are crafted and whether innovative solutions to problems are communicated. Further, by adding a temporal satellite image component to the study, it may be possible to understand how growth in water demands along river systems over time have caused stresses in certain communities.

Research such as this is important in South Asia because it allows us to better link physical world realities with our understanding of the overlapping community and institutional landscapes in a particular region. In the past, NGOs and government agencies have spent tremendous amounts of money trying to assist farmers through the development of large irrigation systems that are found later to perform inadequately (Lam, 1998). Applying techniques developed in this dissertation to efforts such as this one can help us understand the factors that lead to successful, long enduring, community managed irrigation systems

Begin a GIS/Remote Sensing-Based Search for Spatial Anomalies in Forest Governance

Finally, my doctoral studies at Indiana University provided me the opportunity to work on the International Forestry Resources and Institutions (IFRI) program. This research program is active in countries such as Nepal, India, Bolivia, Guatemala, Honduras, Madagascar, Uganda, and others I have learned a great deal from discussions with researchers involved in these efforts

Elinor Ostrom's book *Governing the Commons* provides numerous cases of situations where communities have been able to collectively act and devise well crafted institutions that have overcome "tragedy of the commons" problems. One of the main lessons of the work by Ostrom and other recent common property research is that there are places "out there" where human communities have designed an institutional landscape that protects the resource reasonably well in their particular physical and community landscape configuration.

In the United States, designers of federal policy initiatives often look to the states for creative policy solutions. The logic is that there is a better chance of developing an innovative solution to a problem if all fifty states try their hand at it rather than trying out one single approach at the national level After some time, the state developed solution that appears to work the best may be duplicated at the national level.

At the core of the human dimensions of environmental change research program is the search for institutionally based solutions (a form of policy) that keep human overconsumption or destruction of natural resources in check. But there usually are no easy institutional fixes and often institutional technology transfer fails miserably. There are many examples in development work where a solution devised in one location in the world is applied to another location with a very different physical, community and institutional landscape only to prove to be a complete disaster. Examples exist from all sorts of initiative areas: infrastructure development and maintenance, irrigation, forestry, fisheries–almost any common pool resource setting. Alternatively, there are probably thousands, perhaps even hundreds of thousands of locations in the world where humans have been able to craft and maintain an institutional landscape that somehow manages to keep human consumption of natural resources in check. Like the U.S. federal government learning from state government experiences, we need to do the same at a global scale. We need to develop a method to identify, learn and document innovative institutional landscape solutions to environmental problems. While this is being accomplished, we could and should be developing mechanisms that allow us to determine what range of physical and community landscape settings a particular institutional solution might be appropriate for application. Further, mechanisms are needed to communicate successful endeavors to others.

The IFRI program provides methods to learn about and document innovative institutional solutions (as well as institutional failures) related to forest management. But the IFRI approach, like most field research, is time consuming and can be expensive. A great challenge is how to better select locations for field research. The question here is: Can methods be devised to identify locations that have a high probability that some new, interesting or innovative institutional solution to resource management problems will be discovered? The tools and methods outlined in this volume, particularly the satellite image/GIS processing in Part II provide a real opportunity to do just this. I hope to embark on a future research project to explore how this might be accomplished perhaps in the context of Nepal. Let me outline the initial ideas.

The researcher must first undertake a theoretical endeavor. He or she must identify factors that are thought to influence where humans in a particular context decide to utilize forest resources or convert that land cover for other land uses. Invariably, in Nepal and many other locations, topography will be one of these important factors. In East Chitwan, flat, low lying land adjacent to river systems will have a high likelihood that they will be converted to agriculture land. Adjacency to road networks is another factor likely to raise the probability that a forested area will be converted to other uses. The idea is that through theory and the application of GIS models of the physical (e.g., DEM, road and river networks) and community landscapes (e.g., demographic data and maps depicting in- and out-migration flows) we can begin to identify areas within the physical landscape that have a high probability of being converted from forest to some other land use.[8] A GIS grid coverage of the landscape can be created representing different probability classes. Using land cover classification maps generated from recent at-surface reflectance satellite images, we can identify where forests (or some more extensive age class classification) currently reside. By intersecting the land cover classification map with the conversion probability coverage we can identify forest "spatial anomalies." These are currently forested areas that have a high probability of forest conversion. These would be the candidates for more detailed field research.[9] By applying this satellite image-based change analysis first, we increase the likelihood that the field work will be particularly informative. We stand a better chance of building a database of institutional innovations related to particular physical and community landscape configurations.

The pace of environmental degradation all over the world is in part a result of our inability to devise creative institutional solutions to these problems in a relatively quick manner. Well groomed institutional solutions take time to create, adjust and maintain (Ostrom, 1990). Research can help in that it can make available libraries of institutional solutions that have worked for others to learn from and apply in similar circumstances–a kind of institutional-technology transfer. A longer term project I envision is the development of an "Internet-based expert GIS on forest institutions," perhaps with components of the IFRI database as a foundation, that provides advice and examples related to the crafting and maintenance of forest institutions. Imagine community leaders and policy makers in one small town in the world, accessing this expert GIS over the Internet. Here they specify attributes about their resource management problems, and attributes about their community and particular physical landscape characteristics (including geographic relationships[10]). Picture then the GIS expert system providing users with a description or summary of innovative institutional solutions other communities have crafted who exhibit similar physical and community attributes. One great challenge will be in identifying what constitutes "similar." But the system would not reveal *the* set of institutions to use–many different institutional solutions may be available. Rather, the system would provide information on how other communities from around the world, facing similar problems, developed institutions which effectively solved the problem. These ideas could help spawn creative thinking and problem solving

Instead of having fifty possible creative solutions to a policy problem as we do in the United States federal system example, this system would provide the opportunity to learn from innovative institutional designs of eventually thousands of communities all over the world. A production version of this concept is still a long way away, but as this dissertation shows, we have many of the tools already to be able to turn it into a reality. Endeavors such as these will really move us toward closing or narrowing the information and knowledge gaps that hinder environmental policy-making

Chapter 8 Endnotes

1. For instance, one comparison might be done between forests in Indiana and Missouri. Chile is an example of a South American country that has deciduous forests comparable to what resides in Indiana

2. Group selection is the primary silviculture method in Yellowwood. This method treats smaller areas, allowing neighboring trees to grow and expand their canopies and fill in some of the gaps. I am less sure about the silviculture techniques in Hoosier which, where permitted, appear to still be clearcutting. I expect the reason the Hoosier looks older overall is because most of the forest has been left uncut for the 20-year period.

3. This is one of the tasks my colleagues and I are undertaking in our Indiana Non-industrial Private Forest research described more fully below

4. I am indebted to Glen Green for enlightening me on this issue

5. Excluding the thermal band

6. Parker (1993) argues that scientists focus too much attention on forest regeneration. He feels more emphasis should be placed on "landscape" scale issues such as forest fragmentation.

7. A headwork is the intake point of an irrigation system at its river source.

8. Imagine's model maker would be particularly helpful here

9. For example, in the MSS images in the Indiana scene, there is a large forested area that is owned by the U.S. Government: Jefferson Proving Ground. This area exists in a flat area, with road access and potentially good agricultural land. This area would be readily identified by the procedure described here and if followed by field research would discover its unique reason for remaining forested.

10. This will become less difficult as more topographic maps get converted to standard GIS products such as digital elevation models.

BIBLIOGRAPHY

Abernathy, V 1993. *Population Politics: The Choices that Shape Our Future*: New York. Plenum Press

Adams, J B and Adams, J.D. 1984. "Geologic Mapping Using Landsat MSS and TM Images: Removing Vegetation by Modeling Spectral Mixtures," Third Thematic Conference, Remote Sensing for Exploration Geology, *ERIM*, 2: 615-622.

Adams, J B., Smith, M.O., and Johnson, P.E. 1986. "Spectral Mixture Modeling: A New Analysis of Rock and Soil Types at the Viking Lander I Site." *Journal of Geophysical Research*. 91, B8: 8098-8112.

Adams, B, Smith, M.O., and Gillespie, A.R. 1993. "Image Spectroscopy: Interpretation Based on Spectral Mixture Analysis." In C.M. Pieters and P. Englert (eds.) *Remote Geochemical Analysis: Elemental and Mineralogical Composition*. New York: Cambridge University Press. pp. 145-166.

Adams, J B., Sabol, D., Kapos, V., Filho, R.A., Roberts, D A., Smith, M O. and Gillespie, A.R. 1995. "Classification of Multispectral Images Based on Fractions of Endmembers: Application to Land-Cover Change in the Brazilian Amazon." *Remote Sensing of Environment*. 52: 137-154.

Agrawal, A. 1995. "Population Pressure = Forest Degradation. An Oversimplistic Equation?" *Unasylva*. 186, 46: 50-58

Agrawal, A and Yadama, G.N. 1997. "How Do Local Institutions Mediate Market and Population Pressures on Resources? Forest Panchayats in Kumaon, India." 28: 435-465

Aldhous, P (1993). Tropical deforestation: Not just a problem in Amazonia. *Science*. 259: 1,390

Allen, J 1996. Morgan-Monroe and Yellowwood State Forest Property Manager. Personal Conversation. April 24th.

Allen, J. 1996b. "Factors Affecting Harvest Making Decisions," Yellowwood working document. Indianapolis, IN: IDNR Division of Forestry.

Anderson, M. 1993. "Reforming National Forest Policy: Biological Diversity Should Replace Timber Production as the Primary Guiding Principle for Managing U.S. Forests." *Issues in Science and Technology*. pp. 40-47.

Angelsen, A. (1995). Shifting cultivation and 'deforestation': A study from Indonesia. *World Development*. 23 (10): 1713-1729

Arlinghaus, S.L. (Ed.) 1995. *Practical Handbook of Spatial Statistics*. Boca Raton, Fla: CRC Press.

Ascher, W. (1995). *Communities and Sustainable Forestry in Developing Countries.* ICS Press, San Francisco, Calif.

August, P., J. Michaud, C. Labash, and C. Smith. (1994). GPS for Evironmental Appications: Accuracy and Precision of Locational Dta. *Photogrammetric Engineering and Remote Sensing.* 60 (1). 41-45

Avery, T. E. and Berlin, G. L. 1992. *Fundamentals of Remote Sensing and Air Photo Interpretation.* New York: Macmillan.

Baetson, A. and Curtiss, B. 1996. "A Method for Manual Endmember Selection and Spectral Unmixing," *Remote Sensing of Environment*, 55 229-243.

Barbour, M. G., Burk, J H. and Pitts, W D. 1987. *Terrestrial Plant Ecology*. Menlo Park, California: Benjamin/Cummings Publishers.

Barrett, J.W. 1980. *Regional Silviculture of the United States, Second Edition.* New York: John Wiley and Sons.

Barrett, E C. and Curtis, L.F. 1992. *Introduction to Environmental Remote Sensing.* London: Chapman and Hall.

Becker, C. D., Banana, A., and Gombya-Ssembajjwe, W. 1995. "Early Detection of Tropical Forest Degradation. An IFRI Pilot Study in Uganda." *Environmental Conservation.* 22 (1) (Spring): 31-38

Belward, A.S. 1991. "Spectral Characteristics of Vegetation, Soil and Water in the Visible, Near-Infrared and Middle-infrared Wavelengths." *Remote Sensing and Geographic Infomation Systems for Resource Management in Developing Countries.*pp. 31-53.

Berkes, F. 1992. "Success and Failure in Marine Coastal Fisheries of Turkey." In *Making the Commons Work: Theory, Practice and Policy*, Daniel W. Bromley (ed.) San Francisco: Institute for Contemporary Studies.

Birch, T. W. 1996. *Private Forest-Land Owners of the Northern United States, 1994.* Resource Bulletin NE-136. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Bloomquist, W. 1992. *Dividing the Waters: Governing Groundawater in Southern California*. San Francisco: ICS Press.

Boardman, J.W., Kruse, F.A. and Green, R.O. 1995. "Mapping Target Signatures Via Partial Unmixing of AVIRIS Data." In *Summaries, Fifth JPL Airborne Earth Science Workshop*, JPL Publication 95-1, 1 23-26.

Bouwman, A.F. 1990. "The Effect of Changing Land Cover on the Surface Energy Balance." In A.F. Bouwman (ed.) *Soils and the Greenhouse Effect*. Chichester, John Wiley and Sons.

Brame, S.C. and Henderson, C. 1992. *Wildlife Ethics and Management*. Lander, WY: National Outdoor Leadership School.

Brondizio,E.S., Moran, E.F., Mausel, P. and Wu, Y., 1994. "Land Use Change in the Amazon Estuary: Patterns of Caboclo Settlement and Landscape Management," *Human Ecology*, 22 (3): 249-278.

Brondizio, E., Moran, E., Mausel, P. and Wu, Y. 1996. "Land Cover in the Amazon Estuary: Linking of the Thematic Mapper with Botanical and Historical Data," *Photogrammetric Engineering and Remote Sensing*, 62 (8): 921-929.

Brower, J. E., Zar, J. H. and von Ende, C. N. 1997. *Field and Laboratory Methods for General Ecology*. William C. Brown Publishers.

Brown, J. H. 1994. "Grand Challenges in Scaling Up Environmental Research." In W.K. Michener, J.W. Brunt and S.G. Stafford, (eds.) *Environmental Information Management and Analysis: Ecosystem to Global Scales*. London: Taylor and Francis.

Bruijnzeel, L.A. and Bremmer, C.N. 1989. Highland-Lowland Interactions in the Ganges Brahmaputra River Basin: A Review of Published Literature. ICIMOD Occasional Paper No. 11. ICIMOD: Kathmandu, Nepal.

Campbell, J.B. 1996. *Introduction to Remote Sensing, Second Edition*. New York: The Guilford Press.

Carpenter, S.R. 1989. "Temporal Variance in Lake Communities: Blue-green Algae and the Trophic Cascade." *Landscape Ecology* 3: 175-184.

Caylor, D.A., and O'Leary, J.T. 1995. *Indiana State Forests Recreation Visitor Survey: 1994-1995 Statewide Survey Final Research Report*. Lafayette, IN: Purdue University, Department of Forestry and Natural Resources.

Chambers, R. 1988. *Managing Canal Irrigation: Practical Analysis from South Asia*. Cambridge: Cambridge University Press.

Chavez, P.S. 1989. "Radiometric Calibration of Landsat Thematic Mapper Multispectral Images," *Photogrammetric Engineering and Remote Sensing*, 55: 1285-1294.

Chomitz, K.M., and Gray, D.A. 1995. "Land Use in Southern Belize: A Spatial Model Incorporating Road Endogeneity," Working Paper. Washington, D.C.: World Bank.

Clark, D.L. 1987. *Entrepreneurs in Hardwood*. Indianapolis, IN: White Arts, Inc.

Cleveland, C., Costanza, R., Eggertsson, T., Fortmann, L., Low, B., McKean, M., Ostrom, E., Wilson, J. And Young, O. 1995. "A Framework for Modeling the Linkages Between Ecosystems and Human Systems," Working Paper.

Clary, D.A. 1986. *Timber and the Forest Service*. Lawrence, Kansas: University Press of Kansas.

Cohen, W.B., 1991. "Response of Vegetation Indices to Changes in Three Measures of Leaf Water Stress," *Photogrammetric Engineering and Remote Sensing*, 57: 203-207.

Commons, J. R. 1959. *Legal Foundations of Capitalism*. Madison: University of Wisconsin Press.

Cramer, L., Kennedy, J., Krannich, R., and T., Quigley. 1993. "Changing Forest Service Values and Their Implications for Land Management Decisions Affecting Resource-Dependent Communities." *Rural Sociology*. 58(3): 475-91.

Crawford, S. and Ostrom, E. 1995. "A Grammar of Institutions." *American Political Science Review*. 89, 3: 582-600.

Cubbage, F.W., Regens, J.L., and D.G. Hodges. 1992. "Climate Change and the Role of Forest Policy." In P. N. Nemetz (ed.) *Emerging Issues in Forest Policy*. UBC Press: Vancouver.

Dale, V.H., Mann, L.K., Olson, R.J., Johnson, D.W., and Dearstone, K.C. 1990. "The Long-Term Influence of Past Land Use on the Walker Branch Forest." *Landscape Ecology*. 4 (4): 211-224.

Daubenmire, R. 1974. *Plants and Environment*. New York: Wiley.

Davis, F.W., Quattrochi, D.A., Ridd, M.K., Lam, N. S-N., Walsh, S.J., Michaelsen, J.C., Franklin, J., Stow, D.A., Johannsen, C.J., and Johnson, C.A., 1991. "Environmental Analysis Using Integrated GIS and Remotely Sensed Data: Some Research Needs and Priorities," *Photogrammetric Engineering and Remote Sensing*. 57 (6): 689-697.

de Tocqueville, A. 1945. *Democracy in America*. New York: A.A. Knopf.

Doemel, N.J. (Ed.), 1980. *The Hoosier National Forest: Issues for the 80s*. League of Women Voters of Indiana: Indianapolis, Indiana.

Driver, T.S. and Chapman, G.P. 1996. *Time-scales and Environmental Change*. London: Routledge.

Drury, S.A. 1990. *A Guide to Remote Sensing: Interpreting Images of the Earth*. Oxford: Oxford University Press.

Duffy, D.C. and Meier, A.J. 1992. "Do Appalachian Herbaceous Understories Ever Recover from Clearcutting?" *Conservation Biology*. 6: 196-201.

Duggin, M.J. and Robinove, C.J. 1990. "Assumptions Implicit in Remote Sensing Data Acquisition and Analysis," *International Journal of Remote Sensing*, 11: 1669-1694.

Duncan, D. 1983. "Yellowwood Forest." *Outdoor Indiana*. 48 (5): 30-33.

Dunn C.P., Sharpe, D.P., Guntenspergen, G.R., Stearns, F. and Yang, Z. 1991. "Methods for Analyzing Temporal Changes in Landscape Pattern." In M.G. Turner and R. H. Gardner, (eds.) *Quantitiative Methods in Landscape Ecology*. New York: Springer-Verlag.

Eggertsson, T. 1990. *Economic Behavior and Institutions*. Cambridge: Cambridge University Press.

ENVI, 1996. ENVI Tutorials, ENVI Version 2.5. Boulder, CO: Better Solutions Consulting Limited Liability Company.

ENVI, 1998. "ENVI Tutorial: Multispectral Processing using ENVI's Hyperspectral Tools." http://www.envi-sw.com/e_msihsi.htm, 7 Februrary.

ENVI, 1998. "Advanced Imaging Spectrometer Data Processing and Analysis Using ENVI,Hyperspectral Tutorial #4," http://www.envi-sw.com/e_hsi4.htm. March 3rd.

Everitt, J.H. and Richardson, A.J. 1987. "Canopy Reflectance of Seven Rangeland Plant Species and Variable Leaf Pubescence." *Photogrammetric Engineering and Remote Sensing*, 53, 11: 1571-1575.

Faeth, P., Cort, C. and Livernash, R. 1994. *Evaluating the Carbon Sequestration Benefits of Forestry Projects in Developing Countries*. World Resource Institute.

Fahrig, L And Paloheimo, J. 1988. "Effect of Spatial Arrangement of Habitat Patches on Local Population Size." *Ecology*. 69: 468-475.

Favinger, J 1984a. "A Time of Progress." *Outdoor Indiana* 49 (2): 28-36.

Favinger, J 1984b. "Environmental Era." *Outdoor Indiana* 49 (3) 25-32.

Feit, H A. 1973. "The Ethno-Ecology of the Waswanipi Cree, or How Hunters Can HandleTheir Resources. In Cox, B. (ed.) *Cultural Ecology*. McClelland and Stewart, Toronto.

Firmin-Sellers, K. 1996. *The Transformation of Property Rights in the Gold Coast: An Empirical Analysis Applying Rational Choice Theory* Cambridge: Cambridge University Press.

Fischer, B C 1996. Indiana State Forester Personal communication September 30th.

Fischer, B C 1998. Indiana State Forester. Personal communication February 15.

Fischer, B C , Pennington, S.G., and Tormoehlen, B., 1993 "Public Involvement in Indiana Forestry," *Journal of Forestry*, July: 28-31

Fiorella, M and Ripple, W.J. 1993. "Determining Successional Stage of Temperate Coniferous Forests with Landsat Satellite Data," *Photogrammetric Engineering and Remote Sensing*, 59 (2):239-246

Forman R T T and Godron, M 1986. *Landscape Ecology* New York John Wiley and Sons

Forshaw, M R.B., Haskell, A., Miller, P.F , Stanle, D J., and Townshend, J.R.G. 1983. "Spatial Resolution of Remotely Sensed Imagery: A Review Paper." *International Journal of Remote Sensing*, 4: 497-520.

Fotheringham, A. S. and Rogerson, P. A. 1993. "GIS and Spatial Analytical Problems." *International Journal of Geographic Information Systems*. 7, 1: 3-19.

Fox, J , Kanter, R., Yarnasarn, S., Ekasingh, M. and Jones, R. 1994. "Farmer Decision Making and Spatial Variables in Northern Thailand." *Environmental Management*. 18, 3: 391-399.

Fox, J . Krummel, J. Yarnasarn, S., Ekasingh and Podger, N. 1995 "Land Use and Landscape Dynamics in Northern Thailand: Assessing Change in Three Upland Watersheds." *Ambio*, 24, 6: 328-334.

Gastellu-Etchegorry, J.P. and Sinulingga, A. B. 198 "Designing a GIS For the Study of Forest Evaluation in Central Java." *Tijdschrift voor Econ. En Soc. Geographie*, 79. 93-103

Gibson, C., Ostrom, E. and Ahn, T.K. 1997. "Scaling Issues in the Social Sciences. A Report for the International Human Dimensions Program." Workshop in Political Theory and Policy Analysis, Indiana University

Gibson, C. and Koontz, T. 1998. "When 'Community' Is Not Enough: Institutions and Values in Community-Based Forest Management in Southern Indiana." CIPEC Working Paper. CIPEC, Indiana University.

Gilruth, P.T. Hutchinson, C.F. and Barry, B. 1990. "Assessing Deforestation in the Guinea Highlands of West Africa Using Remote Sensing." *Photogrammetric Engineering and Remote Sensing*. 56, 10: 1375-1392.

Grainger, A. 1993. *Controlling Tropical Deforestation*. London: Earthscan Publications.

Green, G. 1988. *Physical Basis for Remotely Sensed Spectral Variation in a Semi-Arid Shrubland and an Oak-Hickory Forest: Implications for Mapping Soil Types in Vegetated Terrains*. Doctoral Dissertation. St. Louis, Missouri: Washington University, Department of Earth and Planetary Sciences.

Green, G.M. 1996. "Forest Structure and Leaf Spectral Control on Canopy Reflectance. Implications for Geologic Mapping Using Remote Sensing in Forested Terrains." Working Paper. Indiana University, Bloomington. Anthropolgical Center for Training and Research on Global Environmental Change.

Green, G.,M. 1997. Personal conversation about his work studying forests in Missourri. CIPEC, Indiana University

Green, G. Arvidson, R., Sultan, M., and Guinness, E., 1985. "Geobotanical Information Contained in Landsat Thematic Mapper Images Covering Southern Missouri," Paper presented at the Fourth Thematic Conference, "Remote Sensing for Exploratory Geology," San Francisco, California. April 1-4.

Green, G. and Arvidson, R.E. 1986. "Soil Types and Forest Canopy Structures in Southern Missouri: A First Look with AIS Data," In G. Vane and A. Goetz (Eds.) *Proceedings of the Second Airborne Imaging Spectrometer Data Analysis Workshop*. May 6-8. Pasadena, Ca: NASA Jet Propulsion Laboratory.

Green, G.M., Randolph, J.C., and Ostrom, E. 1998. "Leaf to Lampscape: Determining the Seasonal and Inter-Annual Climate Variability Effects on Forest Ecosystems." Proposal submitted to NASA/NSF/DOE/USDA/NOAA Joint Program on

Terrestrial Ecology and Global Change. Center for the Study of Institutions, Population and Environmental Change, Indiana University, Bloomington.

Green, G M and Sussman, R.W 1990 "Deforestation History of the Eastern Rain Forests of Madagascar from Satellite Images." *Science*, 248: 212-215.

Green, G., Schweik, C. and Hanson, M. 1998 "Radiometric Calibration and Atmospheric Correction of Landsat Multispectral Scanner and Thematic Mapper: Guidelines for Global Change Research." Paper submitted to *Environmental Monitoring and Assessment*.

Hackett, S., Schlager, E. and Walker, J. 1994 "The Role of Communication in Resolving Commons Dilemmas: Experimental Evidence With Heterogeneous Appropriator." Working Paper. Workshop in Political Theory and Policy Analysis.

Hall, F G. 1994. "Adaptation of NASA Remote Sensing Technology for Regional-Level Analysis of Forest Ecosystems," in V. A. Sample (Ed.) *Remote Sensing and GIS in Ecosystem Management*. Washington, D C: Island Press

Hall, F G., Strebel, D.E., Nickeson, J.E., and Goetz, S J 1991 "Radiometric Rectification: Toward a Common Radiometric Response Among Multidate, Multisensor Images." *Remote Sensing of Environment*. 35: 11-27.

Hansen, M.H. and Golitz, M.F. 1988 *Timber Resources of the Indiana Knobs Unit, 1986*. Resource Bulletin NC-104. North Central Forest Experiment Station: USDA Forest Service.

Hardin, G 1968. "The Tragedy of the Commons." *Science* 162 1243-8.

Hartke, E J. and Gray, H.H. 1989 *Geology for Environmental Planning in Monroe County, Indiana. Environmental Study 21*. Indiana Department of Natural Resources.

Hayden, B. (1981). Subsistence and ecological adaptations of modern hunter-gatherers. In Harding, R.S.O. and Teleki, G. (eds.), *Omnivorous Primates*. Columbia University Press, New York.

Hedin, L.O. and Likens, G.E. 1996. "Atmospheric Dust and Acid Rain," *Scientific American*, December.

Hill, J. 1991. "A Quantitative Approach to Remote Sensing: Sensor Calibration and Comparison," In A.S. Belward and C.R. Valenzuela (eds.) *Remote Sensing and Geographical Information Systems for Resource Management in Developing Countries*. ECSC, EEC, EAEC: Brussels: 97-110.

Hinnefeld, S 1996. "Bids Opened for Salvage Logging in Forest" *The Herald Times*, December 21. Bloomington, Indiana

Hinnefeld, S 1997 "Anti-logging Activists Arrested at U.S Forest Service Headquarters." *The Herald Times* June 5 Bloomington, Indiana.

Homoya, M.A. 1997. "The Natural Regions of Indiana: An Introduction." In M.T Jackson (ed.) *The Natural Heritage of Indiana*. Bloomington, Indiana: Indiana University Press. pp 158-160.

Homoya, M.A and Huffman, H. 1997. "Sinks, Slopes, and a Stoney Disposition: The Highland Rim Natural Region." In M T Jackson (ed.) *The Natural Heritage of Indiana* Bloomington, Indiana: Indiana University Press pp 167-176.

Huebner, C D., Randolph, J.C. and Parker, G.R 1995. "Environmental Factors Affecting Understory Diversity in Second-Growth Deciduous Forests," *American Midland Naturalist*. 134:155-165.

Huete, A R., Jackson, R.D., and Post, D.F 1984 "Spectral Response of a Plant Canopy with Different Soil Backgrounds," *Remote Sensing of Environment*, 17:37-53.

IDNR, 1997 "Old Growth Forests." http://www ai.org/dnr/naturepr/forests.html (17 February)

IDNR, 1973-1992. *Annual Report* Indianapolis, IN Indiana Department of Natural Resources.

IDNR, 1973 *Annual Report.* Indianapolis, IN Indiana Department of Natural Resources.

IDNR, 1974 *Annual Report.* Indianapolis, IN Indiana Department of Natural Resources

IDNR, 1975 *Annual Report.* Indianapolis, IN Indiana Department of Natural Resources.

IDNR, 1976. *Annual Report.* Indianapolis, IN: Indiana Department of Natural Resources.

IDNR, 1977. *Annual Report.* Indianapolis, IN: Indiana Department of Natural Resources.

IDNR, 1978. *Annual Report.* Indianapolis, IN: Indiana Department of Natural Resources.

IDNR, 1979. *Annual Report.* Indianapolis, IN: Indiana Department of Natural Resources.

IDNR, 1980 *Annual Report.* Indianapolis, IN Indiana Department of Natural Resources.

IDNR, 1986 *Annual Report.* Indianapolis, IN: Indiana Department of Natural Resources.

IDNR, 1987. *Annual Report*. Indianapolis, IN: Indiana Department of Natural Resources.

IDNR Division of Forestry, 1978. *Logging Roads and Skid Trails: A Guide for Soil Protection and Timber Access*. Indianapolis, IN: Indiana Department of Natural Resources, Division of Forestry

IDNR Division of Foresty, 1995. *State Forest Procedures Manual*. Indianapolis, IN: Indiana Department of Natural Resources

IDNR, Division of Forestry, 1996a. "Division of Forestry Properties Section, Strategic Direction, November 1996." Indianapolis, IN: IDNR Division of Forestry.

IDNR Division of Forestry, 1996b. "DNR-Division of Forestry Revenue Source Document."Acquired by Tom Koontz in his interviews with Division officials

IDNR Division of Forestry, 1996c. "Division of Forestry revenue source documentation." Acquired by Tom Koontz in his interviews with Division officials.

IDNR Division of Forestry, 1996d. *Indiana Forestry BMPs: Draft guidelines for review*. Indianapolis, IN: IDNR Division of Forestry.

IDNR, Division of Forestry, 1998a. The Indiana Heritage Trust Program. http://www.dnr.state.in.us/heritage/index.htm. March 10.

IDNR, Division of Forestry,1998b. "Forest Legacy in Indiana." Brochure. Indianapolis: Indiana Department of Natural Resources, Division of Forestry

IDNR, Division of Forestry, 1998c. "Division of Forestry." http://www.dnr.state.in.us/forestry/d-forest.htm. June 12.

IDNR Division of Forestry, 1995. *State Forest Procedures Manual*. Indianapolis, IN: Indiana Department of Natural Resources, Division of Forestry

Idrissi, 1997. *Idrissi Users Guide Version 2.0*. Clark University.

IFRI (International Forestry Resources and Institutions). (1994). *IFRI Data Collection Forms of the Shaktikhor Site, Nepal*. Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington

IGAP, 1998. Indiana Gap Analysis Homepage. http://139.102.7.220/h1/bertha/gap. March 10.

Ives, J. and Messerli, B. 1989. *The Himalayan Dillemma: Reconciling Development and Conservation*. London: Routledge.

Jackson, M.T. 1997. "Perspective: The Indiana That Was," In M.T. Jackson (ed.) *The Natural Heritage of Indiana*. Bloomington, Indiana Indiana University Press. pp. xvii-xxviii.

Jackson, R.D. 1983. "Spectral Indices in N-Space." *Remote Sensing of the Environment*, 13: 409-421.

Jensen, J.R. 1996. *Introductory Image Processing: A Remote Sensing Perspective*. Upper Saddle River, New Jersey: Prentice Hall.

Johnson, L. B. 1990. "Analyzing Spatial and Temporal Phenomena Using Geographic Information Systems: A Review of Ecological Applications." *Landscape Ecology*. 4, 1: 31-43.

Jones, B. 1997. "Buffer Zones Along Streams Vital to Keeping Lake Monroe Clean." *The Herald Times*, 3/14/97.

Justice, C.O., Townshend, J.R.G., Holben, B.N., and Tucker, C.J. 1985. "Analysis of the Phenology of Global Vegetation using Meterological Satellite Data." *International Journal of Remote Sensing*. 6: 1271-1318.

Keller, M., Clark, D.A., Clark, D.B., Weitz, A.M., and Veldkamp, E. 1996. "If a Tree Falls in the Forest..." *Science*, 273: 201.

Kennedy, P. *A Guide to Econometrics*. Cambridge, MA: MIT Press.

Kienast, F. 1993. "Analysis of Historic Landscape Patterns With a Geographic Information System--A Methodological Outline." *Landscape Ecology*. 8, 2: 103-108.

Kimmins, H. 1992. *Balancing Act: Environmental Issues in Forestry*. Vancouver: University of British Columbia Press.

King, G. (1989). "Variance Specification in Event Count Models: From Restrictive Assumptions to a Generalized Estimator." *American Journal of Political Science*. 33 (3): 762-84.

King, G. (1990) *Unifying Political Methodology: The Likelihood Theory of Statistical Inference*. Cambridge University Press, Cambridge.

King, G. (1997). *A Solution to the Ecological Inference Problem: Reconstructing Individual Behavior from Aggregate Data*. Princeton University Press: Princeton.

Knipling, E. "Physical and Physiological Basis for the Reflectance of Visible and Near-Infrared Radiation from Vegetation," *Remote Sensing of Environment*, 1: 155-159.

Kiser, L L. and Ostrom, E 1982. "The Three Worlds of Action. A Metatheoretical Synthesis of Insitutional Approaches " In E Ostrom (ed.) *Strategies of Political Inquiry*, pp 179-222. Beverly Hills Sage

Knight, J 1992. *Institutions and Social Conflict* Cambridge: Cambridge University Press

Koontz, T 1997 *Federalism and National Resource Policy: Comparing State and National Management of Public Forests*. Ph.D Dissertation. Indiana University

Koontz, T., Carlson, L. And Schweik, C. 1998 "The Role of Institutions in Shaping Land Use. An Exploratory Study of Southern Indiana Non-Industrial Private Forests." CIPEC Working Paper CIPEC, Indiana University.

Kornder, S C and Carpenter, J R. 1984. "Application of a Linear Mixing Algorithm to the Normal Alkane Patterns from Recent Salt Marsh Sediments." *Organic Geochemistry*, 1(7) 61-71

Kozlowski, T T., P J Kraemer, and S. G. Pallardy. (1991). *The Physiological Ecology of Woody Plants*. Academic Press, San Diego, Calif.

Kramer, P and Kozolowski, T., 1960. *Physiology of Trees*. New York: McGraw-Hill

Kramer, P and Kozolowski, T 1979. *Physiology of Woody Plants*. New York. Academic Press

Kyoto Protocol, 1998 *Kyoto Protocol to the United Nations Framework Convention on Climate Change* Http //www.unfccc de/fccc/docs/cop3/protocol.pdf (3 March)

Kriebel, R C., 1987 *Plain Ol' Charlie Beam*. Lafayette, IN: Purdue University Press

Lam, W F. 1994. *Institutions, Engineering Infrastructure, and Performance in the Governance and Management of Irrigation Systems: The Case of Nepal*. Ph.D Dissertation. Indiana University, Bloomington, Indiana.

Langston, N. 1995. *Forest Dreams, Forest Nightmares: The Paradox of Old Growth in the Inland West*. Seattle: University of Washington Press.

Larcher, W. 1980. *Physiological Plant Ecology, Second Edition.* Berlin, Springer Verlag.

Lee, C T. and Marsh, S.E. 1995. "The Use of Archival Landsatt MSS and Ancillary Data in a GIS Environment to Map Historical Change in an Urban Riperian Habitat." *Photogrammetric Engineering and Remote Sensing*. 61 (8): 999-1008.

Le Master, D.C. and Rans, L.E. 1997. *Forest Policy Issues in Indiana*. FNR-150. Department of Forestry and Natural Resources. Purdue University Printing Services.

Leopold, A. 1949 [1989]. *A Sand County Almanac: And Sketches Here and There*. New York: Oxford University Press.

Lillesand, T.M. and Kiefer, R.W. 1994. *Remote Sensing and Image Interpretation*. New York: John Wiley and Sons.

Long, J. S. (1997) *Regression Models for Categorical and Limited Dependent Variables*. Sage Publications. Thousand Oaks.

Lovejoy, T. E. (1980). A projection of species extinctions. In Barney, G.O. (ed.), *The Global 2000 Report to the President: Entering the 21st Century*. Council on Environmental Quality, U.S. Government Printing Office, Washington, D.C.

Ludwig, J. A., and J. F. Reynolds. (1980). *Statistical Ecology*. Wiley, New York.

Mahler, A. 1997. "Stop Logging in the National Forests." *The Herald Times*, February 1st.

Malingreau, J.P. 1977. "A Proposed Land-Cover/Land-Use Classification and Its Use With Remote Sensing Data in Indonesia," *Indonesian Journal of Geography*. 7 (33): 5-27.

Malingreau, J.P. and Tucker, C.J. 1988. "Large Scale Deforestation in the Southeastern Amazon Basin of Brazil. *Ambio*. 17,1: 49-54.

Markham, B.L. and J.L. Barker. 1986. "Landsat MSS and TM Post-Calibration Dynamic Ranges, Exoatmospheric Reflectances and At-Satellite Temperatures," EOSAT Technical Notes. August.

Marsh, S.E., Walsh, J.L., and Hutchinson, C.F., 1990. "Development of an Agricultural Land-Use GIS for Sengal Derived From Multispectral Video and Photographic Data," *Photogrammetric Engineering and Remote Sensing*. 56 (3): 351-357.

Mathis, R. 1936. "Brown County History," Masters Thesis. Bloomington, IN: PIP Printing.

Mausel, P., Wu, Y., Li, E., Moran, E.F., and Brondizio, E.S., 1993. "Spectral Identification of Successional Stages Following Deforestation in the Amazon," *Geocarto International* (4): 61-71

McCleerey, E.M., 1977. "Tree Planting for Erosion Control." *Outdoor Indiana*. 42 (8): 37-38.

McCracken, S.D., Safar, C.A.M., and Green, G. 1997. "Deforestation and Forest Regrowth in Indiana, 1860-1990: A Socio-Demographic Perspective. Paper presented at the Annual Meetings of the Population Association of America, Washington, D.C., March 26-28, 1997.

McGarigal, K. and Marks, B. J. 1994. *Fragstats: Spatial Pattern Analsysis Program for Quantifying Landscape Structure*. Forest Science Department, Oregon State University.

McGrew, J.C. and Monroe, C.B. 1993. *An Introduction to Statistical Problem Solving in Geography*. Dubuque, Iowa: Wm C. Brown.

McKean, Margaret A. (1992). Management of Traditional Common Lands (Iriaichi) in Japan. In Bromley, D.W. et al (eds.) *Making the Commons Work: Theory, Practice, and Policy*. ICS Press, San Francisco

Meadows, D.H., 1990. "Biodiversity: The Key to Saving Life on Earth." *Land Stewardship Letter*. Summer. pp. 4-5.

Meffe, G.K. and Carrol, C.R. 1994. *Principles of Conservation Biology*. Sunderland, MA: Sinauer Associates.

Metz, J.J. 1990. "Forest-Product Use in Nepal." *The Geographic Review*. 80, 3.

Meyers, N. 1988. "Tropical Forests and Their Species: Going, Going ..." In E.O. Wilson and F. M. Peter (eds.) *Biodiversity*. Washington, D.C.: National Academy Press. Pp. 28-35.

Miller, G. 1992. *Managerial Dilemmas*. Cambridge: Cambridge University Press.

Millette, T.L., Tuladhar, A.R., Kasperson, R.E., and Turner II, B.L. 1995. "The Use and Limits of Remote Sensing for Analysing Environmental and Social Change in the Himalayan Middle Mountains of Nepal." *Global Environmental Change*. 5 (4): 367-380.

Moran, E.F., Brondizio, E. and Mausel, P. 1994a. "Monitoring Secondary Succession and Land-Use Change in Amazonia." *National Geographic Research and Exploration*, 19: 458-476.

Moran, E.F., Brondizio, E. and Mausel, P. 1994b. "Secondary Succession." *National Geographic Research and Exploration*. 10 (4): 458-476

Moran, E.F., Brondizio, E., Mausel, P and Wu, Y 1994c. "Integrating Amazonian Vegetation, Land-Use, and Sattelite Data." *Bioscience* 44 329-338

Morrow, C. E., and R.W Hull. (1996). "Donor-Initiated Common Pool Resource Institutions: The Case of the Yanesha Forestry Cooperative." *World Development* 24(10): 1641-1657

Moss, M R. and Davis, L S 1994. "Measurement of Spatial Change in the Forest Component of the Rural Landscape of Southern Ontario." *Applied Geography* 14,3: 214-231

Myers, N (1988) Tropical forests and their species: Going, going..." In Wilson, E O and Peter, F M (eds). *Biodiversity*. National Academy Press, Washington, D C

Myers, N. 1994. "Tropical Deforestation. Rates and Patterns." In K. Brown and D W Pierce (eds) *The Causes of Tropical Deforestation*. Vancouver, UBC Press 27-40

Naiman, R.J., Bisson, P A., Lee, R.G., and Turner, M.G. 1997 "Approaches to Management at the Watershed Scale." in K.A. Khom and J.F Franklin (Eds) *Creating a Forestry for the 21st Century: The Science of Ecosystem Management* Washington, D.C : Island Press. pp. 239-253

NALC. 1997. "North American Landscape Characterization." Http://edcwww.cr.usgs.gov/glis/hyper guide/nalc, April 4

Nash, R 1982. *Wilderness and the American Mind*. New Haven Yale University Press

Niskanen, W. 1971 *Bureaucracy and Representative Government*. Chicago, IL Aldine and Atherton

Nordhausen, M. 1912 "Uber Sonnen und Schattenblatter," Ber Dtsch. Bot Ges 30 483-503.

Norton, B. J. (ed.) (1986). *The Preservation of Species*. Princeton University Press, Princeton, N J.

Ostrom, E. 1986a. "An Agenda for the Study of Institutions." *Public Choice* 48 3-25

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.

Ostrom, E. 1992. *Crafting Institutions for Self-Governing Irrigation Systems* San Francisco ICS Press.

Ostrom, E. 1997 "Self-Governance and Forest Resources," Paper presented at the conference on "Local Institutions for Forest Management: How Can Research Make a Difference," Center for International Forestry Research (CIFOR), Bogor, Indonesia, 19-21, 1997

Ostrom, E. (1997) What Makes for Successful Institutions to Govern Common Pool Resources Paper presented at the conference on "Local Institutions for Forest Management: How Research Can Make a Difference," Center for International Forestry Research (CIFOR), Bogor, Indonesia, November 19-21, 1997.

Ostrom, E., Gardner, R. and Walker, J. 1994 *Rules, Games and Common Pool Resources*. Ann Arbor: The University of Michigan Press.

Ostrom, E. and Wertime, M.B. (1995) IFRI research strategy. Working paper. Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington.

Ostrom, E. et al (1994). *IFRI Coding Forms*. Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington.

Ostrom, V 1980 "Artisanship and Artifact." *Public Administration Review* 40:309-317

Ostrom, V. 1991 *The Meaning of American Federalism: Constituting a Self-Governing Society*. San Francisco, CA ICS Press.

O'Toole, R. 1988 *Reforming the Forest Service*. Island Press Washington, D.C.

Outdoor Indiana, 1935a. "Establishment of National Forest in Southern Indiana is Authorized." *Outdoor Indiana*, II (1): 3, 40

Outdoor Indiana, 1935b. "Creating Eleven Artificial Lakes, Covering 300 Acres, on State Lands." *Outdoor Indiana*, II (5): 8-9.

Outdoor Indiana, 1935c. "Establishment of National Forest in Southern Indiana is Authorized." *Outdoor Indiana*, 2 (1): 3, 40.

Outdoor Indiana, 1938. "Bean Blossom Area is Dedicated to Public Use, Conservation Program." *Outdoor Indiana*, V (10): 8, 27.

Pace, S., *et al.*, 1995. *The Global Positioning System: Assessing National Policies*. Rand Corporation.

Paine, D.P. 1981. *Aerial Photography and Image Interpretation for Resource Management*. New York: Wiley.

Pardo, R. 1993 Back to the Future. Nepal's New Forestry Legislation *Journal of Forestry, 91: 22-26.*

Parker, G R 1997 "The Wave of Settlement," In M T. Jackson (ed.) *The Natural Heritage of Indiana.* Bloomington, Indiana: Indiana University Press. pp. 369-382.

Peterjohn, W T and Correll, D.L. 1984 "Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riperian Forest" *Ecology* 65 1466-1475

Pickett, S T A. and Cadenasso, M. L. 1995 "Landscape Ecology: Spatial Heterogeneity in Ecological Systems." *Science* 269 331-334.

Pielou, E.C. 1974 *Population and Community Ecology.* New York: Gordon and Breach.

Pimental, D , Harman, R., Pacenza, M., Pecarsky, J., and Pimental, M. 1994. "Natural Resources and an Optimal Human Population." *Population and Environment.* 15, 5 347-69

Poffenberger, M 1990 *Keepers of the Forest: Land Management Alternatives in Southeast Asia* West Hartford, CT Kumarian Press.

Price, J C 1987 "Calibration of Satellite Radiometers and Comparison of Vegetation Indices," *Remote Sensing of Environment* 18: 35-48

Prince, S D 1991 "Satellite Remote Sensing of Primary Production Comparison of Results for Sahelian Grasslands, 1981-1988." *International Journal of Remote Sensing* 12:1313-1330.

Radue, A 1998 GIS Lab Manager, Midwest Center for the National Institute of Global Environmental Change, School of Public and Environmental Affairs, Indiana University, Bloomington. Personal conversation.

Randolph, J C 1993. *Forest Ecology and Management.* Forest Ecology Lab Manual, School of Public and Environmental Affairs, Indiana University, Bloomington.

Reid, W. V., and Miller, K.R. (1989). *Keeping Options Alive: The Scientific Basis for Conserving Biodiversity.* World Resources Institute, Washington, D C.

Repetto, R. (1988). *The Forest for the Trees? Government Policies and the Misuse of Forest Resources.* World Resources Institute, Washington, D C

Repetto, R 1988 "Subsidized Timber Sales from National Forest Lands in the United States." In R. Repetto and M. Gillis (eds.) *Public Policies and the Misuse of Forest Resources.* Cambridge: Cambridge University Press.

Richards, J.A. 1986. *Remote Sensing Digital Image Analysis: An Introduction.* New York: Springer Verlag.

Richards, J. F., and Tucker, R.P. (eds.) (1988) *World Deforestation in the Twentieth Century.* Duke University Press, Durham, N.C.

Robinove, C.J. 1982. "Computation with Physical Values from Landsat Digital Data." *Photogrammetric Engineering and Remote Sensing*, 48 (5): 781-784.

Rockwell, R. C. 1994. "Culture and Cultural Change," In W. B. Meyer and B. L. Turner II (Eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge: Cambridge University Press.

Root, T.L. and Schneider, S.H. 1995. "Ecology and Climate: Research Strategies and Implications." *Science.* 269: 334-341

Rosenbaum, W. A. 1985. *Environmental Politics and Policy.* CQ Press: Washington, D.C.

Ryszkowski, L. and Kedziora, A. 1987. "Impact of Agriculture Landscape Structure on Energy Flow and Water Cycling." *Landscape Ecology.* 1: 85-94.

Sabol, D.E. Jr., Adams, J.B., and Smith, M.O., 1992. "Quantitative Subpixel Spectra Detection of Targets in Multispectral Images." *Journal of Geophyiscal Reseaurch,* 97 (E2): 2659-2672

Sader, S.A. 1995. "Spatial Characteristics of Forest Clearing and Vegetation Regrowth as Detected by Landsat Thematic Mapper Imagery." *Photogrammetric Engineering and Remote Sensing.* Vol. 61, No. 9: 1145-1151.

Sader, S., Waide, R.B., Lawrence, W.T., and Joyce, A.T., 1989. "Tropical Forest Biomass and Successional Age Class Relationships to a Vegetation Index Derived from Landsat TM Data," *International Journal of remote Sensing,* 17(1): 9-27.

Sader, S.A. and Wynne, J.C., 1992. "RGB-NDVI Color Composites for Visualizing Forest Change Dynamics," *International Journal of Remote Sensing, 13:3055-3067.*

Sample, V. A. (Ed.) 1994. *Remote Sensing and GIS in Ecosystem Management.* Washington, D.C.: Island Press.

Sayn-Wittgenstein, L. 1961. "Recognition of Tree Species on Aerial Photography by Crown Characteristics." *Photogrammetric Engineering.* 27, 5: 792-809.

Schein, E.H. 1985. *Organizational Culture and Leadership*, Jossey-Bass: San Francisco.

Schlager, E. 1990. *Model Specifications and Policy Analysis: The Governance of Costal Fisheries*. PhD Dissertation. Indiana University.

Schreier, H. and Brown, S. 1992. "GIS Approaches to Resolve Conflicts in the Himalayas," *Geo Info Systems*, 2 (9) 52-56,

Schweik, C. M., 1997. "Spatial Analysis of Natural Resources in East Chitwan, Nepal: Conceptual Issues and a Multiscale Research Program." In, G. Shivakoti, G. Varughese, E. Ostrom, A. Shukla, and G. Thapa (eds.) *People and Participation in Sustainable Development: Understanding the Dynamics of Natural Resource Systems*. Proceedings of an International Conference, 17-21 March 1996, Institute of Agriculture and Animal Science, Tribuvan University, Rampur, Chitwan, Nepal.

Schweik, C. M., Adhikari, K. R., and Pandit, K. N. 1997. "Land-Cover Change and Forest Institutions: A Comparison of Two Sub-basins in the Siwalik Hills of Nepal." *Mountain Research and Development*, 17 (2) 99-116.

Scott, J.M., Davis, F., Csuti, B., Noss, R., Butterfield, B., Groves, C., Anderson, H., Caicco, S., D'Erchia, F., Edwards, T.C., Ulliman, J. and Wright, R.G. 1993. "Gap Analysis: A Geographic Approach to the Protection of Biological Diversity," *Wildlife Monographs*, 123

Shaw, G. and Wheeler, D. 1994. *Statistical Techniques in Geographical Analysis*. New York: Halsted Press.

Shields, L. 1950. "Leaf Xeromorphology as Related to Physiological and Structural Influences," *Botanical Review*, 16. 399-477.

Shimabukuro, Y. E., and Smith, J.A., 1995. "Fraction Images Derived from Landsat TM and MSS Data for Monitoring Reforested Areas," *Canadian Journal of Remote Sensing*, 21 (1). 67-74.

Shukla, A. K., Gajurel, K. P., Shivakoti, G., Poudel, R., Pandit, K. N., Adhikari, K. R., Thapa, T. B., Shakya, S. M., Yadav, D. N., Joshi, N. R. and Shretha, A. P. 1993. *Irrigation Resource Inventory of East Chitwan*. IMSSG, IAAS, Rampur, Chitwan.

Shrestha, B.K. 1993. *A Himalayan Enclave in Transition: A Study of Change in the Western Mountains of Nepal*. Kathmandu: International Center for Integrated Mountain Development.

Shrestha, R. (1996). IFRI Team leader, Personal communication, (June).

Sieber, E., and Munson, C.A., 1992. *Looking at History: Indiana's Hoosier National Forest Region, 1600 to 1950*. United States Department of Agriculture Forest Service

Siegal, B.S. and Gillespie, A.R., 1980. *Remote Sensing in Geology*. New York: John Wiley and Sons.

Simpson, J. 1997. "Lifeblood of the Land: Water." In M.T. Jackson (ed.) *The Natural Heritage of Indiana*. Bloomington, Indiana: Indiana University Press. pp. 59-65.

Singer, R.B. 1979. "Mars: Large Scale Mixing of Bright and Dark Surface Materials and Implications for Analysis of Spectral Reflectance," *Proceedings of the 10th Annual Lunar Planetary Science Conference*. pp. 1835-1848.

Smith, D.M. 1962. *The Practice of Silviculture*. New York: John Wiley and Sons.

Smith, E.A. 1983. "Anthropological Applications of Optimal Foraging Theory: A Critical Review." *Current Anthropology*, 24(5): 625-52.

Smith, M.O., Ustin, S.L., Adams, J.B., and Gillespie, A.R. 1990a. "Vegetation in Deserts: I. A Regional Measure of Abundance from Multispectral Images," *Remote Sensing of Environment*, 31:1-26.

Smith, M.O., Ustin, S.L., Adams, J.B., and Gillespie, A.R. 1990b. "Vegetation in Deserts: II. Environmental Influences on Regional Abundance," *Remote Sensing of Environment*, 31:27-52.

Smith, W.B., and Golitz, M.F. 1988. *Indiana Forest Statistics, 1986*. Resource Bulletin NC-108. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Spencer, J.S. Jr., Kingsley, N.P., and Mayer, R.V. 1990. *Indiana's Timber Resource, 1986: An Analysis*. Resource Bulletin NC-113. St. Paul, MN: United States Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Spurr, S.H. and Barnes, B.V. 1992. *Forest Ecology*. Malabar, FL: Krieger Publishing Company.

Starr, J. and Estes, J. 1990. *Geographic Information Systems: An Introduction*. Englewood Cliffs, NJ: Prentice Hall.

Stein, Brenda. 1998. Morgan-Monroe-Yellowwood State Forester. "Morgan-Monroe History," Personal e-mail (5 Feburary).

Steininger, M.K. 1996. "Tropical Secondary Forest Regrowth in the Amazon: Age, Area and Change Estimation with Thematic Mapper Data, *International Journal of Remote Sensing*, 17(1): 9-27.

Stone, T.A., Brown, I.F., and Woodwell, G.M. 1991. "Estimation by Remote Sensing of Deforestation in Central Rondonia, Brazil." *Forest Ecology and Management* 38 (3-4). 291-304.

Storrs, A., and Storrs, J. (1990). *Trees and Shrubs of Nepal and the Himalayas*. Pilgrims Book House, Kathmandu.

Stringer, W.J., Groves, J.E. and Olmsted, C. 1988. "Landsat Determined Geographic Change." *Photogrammetric Engineering and Remote Sensing* 54: 347-351.

Tang, S. Y. 1992. *Institutions and Collective Action: Self-Governance in Irrigation*. San Francisco: ICS Press.

Task Force on Global Biodiversity, Committee on International Science. (1989). *Loss of Biological Diversity: A Global Crisis Requiring International Solutions*. National Science Board, Washington, D.C.

Teillet, P.M. and Fedosejevs, G. 1995. "On the Dark Target Approach to Atmospheric Correction of Remotely Sensed Data." *Canadian Journal of Remote Sensing*, 21 (4). 374-387.

Thapa, G.B. and Weber, K.E. 1990. *Managing Mountain Watersheds: The Upper Pokhara Valley, Nepal*. Asian Institute of Technology: Bangkok, Thailand.

Thomas, W. L. Jr., (ed.) 1956. *Man's Role in Changing the Face of the Earth*. Chicago: University of Chicago Press.

Thomson, J. T., Feeny, D. and Oakerson, R.J. 1992. Institutional Dynamics: The Evolution and Dissolution of Common-Property Resource Management." In Bromley, D.W. et al.(eds.), *Making the Commons Work: Theory, Practice, and Policy*. ICS Press, San Francisco.

Thompson, W.A., Pearse, P.H., Van Kooten, G.C. and Vertinsky, I. 1992. "Rehabilitating the Backlog of Unstocked Forests Lands in British Columbia: A Preliminary Simulation Analysis of Alternative Strategies." In Peter N. Nemetz (ed.) *Emerging Issues in Forest Policy*. Vancouver: University of British Columbia Press.

Townshend, J.R.G. and Tucker, C.J. 1984. "Objective Assessment of Advanced Very High Resolution Radiometer Data for Land Cover Mapping." *International Journal of Remote Sensing*, 9,2:497-50

Trotter, C. M. 1991. "Remotely Sensed Data as an Information Source for Geographical Information Systems in Natural Resource Management: A Review." *International Journal of Geographic Information Systems*. 5, 2: 225-239.

Tucker, C J., Townsend, J.R.G., and Gott, T.E. 1985. "African Land-Cover Classification Using Satellite Data." *Science* 227 (4685) 369-75

Tucker, C J., VanPraet, C.L., Sharman, M J., and Van Ittersum, G 1985 Missing Title. *Remote Sensing of Environment*, 17 233-249

Turner, B L., 1998 Professor of Geography, Clark University. Personal Conversation, February 22.

Turner, M. 1987 "Land Use Changes and Net Primary Production in the Georgia Landscape 1935 to 1982." *Environmental Management*. 11 237-247

Turner, M G 1990 "Spatial and Temporal Analysis of Landscape Patterns" *Landscape Ecology* 4,1 21-30.

Turner, M., Dale, V. H. and Gardner, R.H. 1989 "Predicting Across Scales Theory Development and Testing." *Landscape Ecology* Vol. 3 (3/4) 245-252.

Turner, M G and Gardner, R. H. 1991 *Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity*. New York Springer-Verlag

Turner, P 1995 "Explaining Deforestation: A Preliminary Review of the Literature." Working Paper #W95I-17 Indiana University, Bloomington Workshop in Political Theory and Policy Analysis

Turner II, B L and Meyer, W.B. 1994 "Global Land-Use and Land-Cover Change: An Overview" In W. B. Meyer and B. L. Turner II (Eds.) *Changes in Land Use and Land Cover: A Global Perspective*. Cambridge: Cambridge University Press.

Turner II, B.L., Moss, R.H. and Skole, D.L. 1993. *Relating Land Use ad Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project*. Stockholm, International Geosphere-Biosphere Programme.

Turney, R. 1998. Hoosier National Forest Planner. Personal Conversation, May 28th, 1998.

Ustin, S.L., Smith, M.O. and Adams, J.B. 1993. "Remote Sensing of Ecological Processes: A Strategy for Developing and Testing Ecological Models Using Spectral Mixture Analysis," In J. Ehleringer and C. Field (Eds.) *Scaling Physiological Processes: Leaf to Globe*. pp. 339-357.

Umans, L 1993. The Unsustainable Flow of Himalayan Fir Timber *Mountain Research and Development*. 13(1): 73-88.

Unruth, J.D. 1994. "The Role of Land Use Pattern and Process in the Diffusion of Valuable Tree Species." *Journal of Biogeography*. 21: 283-295.

USDA Forest Service. 1973. "Timber Sale Contract. FS-2400-6T."

USDA Forest Service. 1985a. *Land and Resource Management Plan, Hoosier National Forest*. U.S. Department of Agriculture, Forest Service, Eastern Region.

DA Forest Service, 1985b. *Final Environmental Impact Statement, Hoosier National Forest*. U.S. Department of Agriculture, Forest Service, Eastern Region.

USDA Forest Service, 1985c. *Hoosier National Forest: Record of Decision*. U.S. Department of Agriculture, Forest Service, Eastern Region.

USDA Forest Service, 1991a. *Record of Decision, Hoosier National Forest*. U.S. Department of Agriculture, Forest Service, Eastern Region.

USDA Forest Service, 1991b. *Plan Amendment, Hoosier National Forest*. U.S. Department of Agriculture, Forest Service, Eastern Region.

USDA Forest Service, 1996. *Environmental Assessment, Pleasant Run Emergency Hardwood Salvage Project*. U.S. Department of Agriculture, Forest Service, Eastern Region.

USDA Forest Service, no date. "Introduction to the Pleasant Run Unit of the Brownstown Ranger District, Hoosier National Forest." Document received at Hoosier National Forest Headquarters, Bedford, IN: 2p.

USFWS, 1998. National Wetlands Inventory Program. http://www.nwi.fws.gov. March 10.

USGS, 1997. "North American Landscape Characterization," http://edcwww.cr.usgs.gov/glis/hyper/guide/nalc#nalc2. September 8th.

Ustin, S.L., Smith, M. O., and Adams, J.B., 1993. "Remote Sensing of Ecological Processes: A Strategy for Developing and Testing Ecological Models Using Spectral Mixture Analysis," In J. Ehleringer and C. Field (Eds.) *Scaling Physiological Processes: Leaf and the Globe*, New York, NY: Academic Press.

Van Dorp, D. and Opdam, P.F.M. 1987. "Effects of Patch Size, Isolation and Regional Abundance on Forest Bird Communities." *Landscape Ecology*. 1: 59-73.

Verbyla, D.L. 1995. *Satellite Remote Sensing of Natural Resources*. Boca Raton: Lewis Publishers.

Walter, H. and Breckle, S. 1985 *Ecological Systems of the Biosphere*. Berlin: Springer-Verlag.

Westman, W. E., Strong, L.L., and Wilcox, B.A. 1989 "Tropical Deforestation and Species Endangerment: The Role of Remote Sensing," *Landscape Ecology* 3 (2): 97-109.

Widner, R.R. 1966. *Forests and Forestry in the American States*. The National Association of State Foresters.

Wilkie, D.S. and Finn, J.T. 1996. *Remote Sensing Imagery for Natural Resources Monitoring: A Guide for First-Time Users*. New York: Columbia University Press.

Wilkinson, C.F. and Anderson, H. M. 1985. "Land and Resource Planning in the National Forests." *Oregon Law Review*, Vol. 114, Nos. 1 and 2.

Wilcox, R. 1951. "The State Forests of Indiana." *Outdoor Indiana*, 18 (8): 2, 21.

Wilcox, R., and Shaw, T.E. 1935. *Planting Forest Trees in Indiana*. Indianapolis, IN: The Department of Conservation, Division of Forestry.

Williams, J.T. 1995. "Electoral Institutions and Public Policy: Distributive Politics and Capital Improvement Projects," Research Proposal Funded by the National Science Foundation, 1995-1998. Indiana University, Bloomington.

Winterhalder, B. (1993). Work, resources and population in foraging societies. *Man*, 28: 321-40.

Wolman, M.G. and Fournier, F. G. A. (eds.) 1987. *Land Transformation in Agriculture*. Chichester: John Wiley and Sons.

Wolter, P.T., Mladenoff, D.J., Host, G.E., and Crow, T.R. 1995. "Improved Forest Classification in the Northern Lake States Using Multi-Temporal Landsat Imagery." *Photogrammetric Engineering and Remote Sensing*. 61 (9): 1129-1143.

Woodwell, G.M., Houghton, R.A., Stone, T.A., and Park, A.B. 1986. "Changes in the Area Forests in Rondonia, Amazon Basin, Measured by Satellite Imagry. In J.R. Trabalka and D.E. Reichle (eds.) *The Changing Carbon Cycle, A Global Analysis*. New York: Springer-Verlag

World Resources Institute, 1986. *World Resources, 1986: An Assessment of the Resource Base That Supports the Global Economy*. New York: Basic Books.

Zumeta, D.C. 1980. "Indiana's Forest Resource Planning," *Outdoor Indiana*. 44 (10): 32.

Zumeta, D.C. 1981. *Indiana Forest Resource Management Guide Summary*. Indianapolis, IN: Indiana Department of Natural Resources, Division of Forestry.

Charles M. Schweik
Center for Institutions, Population and Environmental Change
Indiana University
408 N. Indiana
Bloomington, IN 47408
E-mail: cschweik@indiana.edu
http://php.indiana.edu/~cschweik/home.htm
Phone: 812-855-2230 Fax: 812-855-2564

Home:
58 North East Street
Building 6 Apartment 4
Amherst, MA 01002

EDUCATION

1998 (August) — Ph.D. in Public Policy,
School of Public and Environmental Affairs, and the Department of Political Science, Indiana University, Bloomington

Fields: Public Policy (Environmental Policy, Domestic and South Asian Forest Management), Public Management (Management Information Systems, Geographic Information Systems), Methodology (Quantitative Methods, Institutional Analysis)

Dissertation: The Spatial and Temporal Analysis of Forest Resources and Forest Institutions

Chair: Professor Elinor Ostrom

1991 — Maxwell School of Citizenship and Public Affairs, Syracuse University
Masters of Public Administration (M.P.A.), Concentration in Public Management.

1984 — Potsdam State University, Potsdam, New York
Bachelor of Arts (B.A.), Computer Science, summa cum laude

PUBLICATIONS

"Land-cover Change and Forest Institutions: A Comparison of Two Sub-basins in the Siwalik Hills of Nepal." 1997. *Mountain Research and Development*, Vol. 17 (2): 99-116 (with K.R. Adhikari and K.N. Pandit).

"The Spatial Analysis of Natural Resources in East Chitwan, Nepal: Conceptual Issues and a Multi-Scale Research Program." 1997. In G. Shivakoti, *et al.* (Eds.) *People and Participation in Sustainable Development: Understanding the Dynamics of Natural Resource Systems.* Proceedings of an international conference held at the Institute of Agriculture and Animal Science, Rampur, Chitwan, Nepal, March 17-21, 1996. pp. 219-34.

"Integration of GIS and GPS Techniques in Irrigation and Forest Resources Mapping: Lessons Learned." 1997. In G. Shivakoti, *et al.* (Eds.) *People and Participation in Sustainable Development: Understanding the Dynamics of Natural Resource Systems.* Proceedings of an international conference held at the Institute of Agriculture and Animal Science, Rampur, Chitwan, Nepal, March 17-21, 1996. pp. 191-204 (with K.R. Adhikari and K.N. Pandit)

"Social Norms and Human Foraging: An Investigation into the Spatial Distribution of Shorea robusta in Nepal." 1996. *Food and Agriculture Organization Working Paper Series: Forest Trees and People Program. Phase II.*

"Electronic Mail, Privacy and the Public Sector: Guidelines for Public Employees and Organizations." 1995. *The Employee Responsibility and Rights Journal*, December.

"A Relational Archive for Natural Resources Governance and Management." 1994. In A. Singh (ed.) *Proceedings of the UNEP and IUFRO International Workshop in Cooperation with FAO on Developing Large Environmental Databases for Sustainable Development*. July 14-16. Nairobi, Kenya. Sioux Falls, SD: UNEP (with E. Ostrom, S. Huckfeldt, M.B. Wertime).

PAPERS UNDER REVIEW

"Radiometric Calibration of Landsat Multispectral Scanner and Thematic Mapper Images: Guidelines for the Global Change Community." 1998. Submitted to *Remote Sensing of Environment*. (Coauthored with Glen Green and Mark Hanson)

"Using Spatial Information to Understand Forest Change and Human Dynamics: A Case from Nepal," 1998. Under review, *Environmental Monitoring and Assessment.*

"The Use of Spectral Mixture Analysis to Study Human Incentives, Actions and Environmental Outcomes." 1998. Submitted to the Social Science Computer Review. (Coauthored with Glen Green).

SELECTED WORKING PAPERS AND PRESENTATIONS

"Radiometric Calibration of Landsat Multispectral Scanner and Thematic Mapper Images: Guidelines for the Global Change Community." Presentation to National Science Foundation External Review Board, CIPEC Annual Review, February 1998.

"CIPEC Geographic Information Systems and Institutional Analysis Research in Nepal." Presentation to Members of the National Planning Commission and the Ministry of Local Development, His Majesty's Government, Nepal during their visit to Indiana University, August 1, 1997.

"The Center for Institutions, Population and Environmental Change." Presentation to the director and staff of the Indiana Department of Natural Resources, Division of Forestry, Indiana University, February, 26, 1997.

"The Relationship of Forest Management and Forest Vegetation: Linking Remote Sensing and Institutional Analysis." 1996. Working paper. Paper presented at the Center for Institutions, Population and Environmental Change, Indiana University, during National Science Foundation site review.

"Acceptance of a New Computer Based Communications Technology: A Case Study of Asynchronous Computer Conferencing." Technology and Information Policy Program, Syracuse University, Working Paper 91-25, January, 1991.

GRANT PARTICIPATION

Co-wrote and awarded a grant from the Ford Foundation, New Delhi (with Principal Investigator Elinor Ostrom) entitled "Nepal Irrigation and Institutions and Systems III".

Wrote "The Workshop in Political Theory and Policy Analysis Geographic Information Systems Activities." as a presentation made to the National Science Foundation site selection committee visiting Indiana University for possible funding of the Center for Institutions, Population and Environmental Change, Indiana University. IU was awarded a grant to start the Center.

AWARDS (See also Teaching Experience)

Outstanding Teacher/Scholar Fellowship. Summer 1998. College of Arts and Sciences, Indiana University, Bloomington, Indiana.

Dissertation Fellowship. Academic year 1997-98. Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington, IN.

Second prize, American Society for Public Administration's student paper contest. 1991. Paper title "Electronic Mail, Privacy and the Public Sector Workplace: Guidelines for Public Employees."

Graduate Scholar. 1989-1990. Maxwell School of Citizenship and Public Affairs, Syracuse University, Syracuse NY.

IBM Corporate Headquarters Award for Excellence and Achievement. May 1989. IBM Corporate Headquarters, Southbury, CT.

IBM Division Award. April, 1989. IBM General Technology Division, East Fishkill, NY.

CONFERENCES

"Linking Satellite Images to Land Use Activities: An Exploratory Study of Southern Indiana Non-Industrial Private Forests," coauthored with Dr. Tomas Koontz and Laura Carlson. 1998 Western Political Science Association Meeting, Fort Collins, Colorado.

"Using Spatial Information to Understand Forest Change and Community Dynamics: A Case From Nepal," 26th Annual Conference on South Asia, Center for South Asia, University of Wisconsin at Madison, October 16-20, 1997.

"The Spatial Analysis of Natural Resources in East Chitwan, Nepal: Conceptual Issues and a Multi-Scale Research Program," Paper Presented at the Conference on "Participation, People, and Sustainable Development: Understanding the Dynamics of Natural Resource Systems," Institute of Agriculture and Animal Sciences (IAAS), Central Campus, Rampur, Chitwan, Nepal, March 17-20, 1996.

Discussant, "Data Collection Methods and Tools" panel at the National Seminar on Improving Support Services to Farmer-Managed Irrigation Systems (FMIS), Kathmandu, Nepal, September 1-2, 1994.

"A Relational Archive for Natural Resources Governance and Management," Application of Advanced Information Technologies: Effective Management of Natural Resources, At the Conference of the American Society of Agricultural Engineers, Spokane, Washington, June 8-19, 1993.

RESEARCH EXPERIENCE

August 1998 Post Doctoral Fellow, **Center for Institutions, Population and Environmental Change, Indiana University**, Bloomington.

June 1996- August 1998	Research Assistant, **Center for Institutions, Population and Environmental Change, Indiana University**, Bloomington. Responsible for the planning and project lead role of an eight member research group studying forest change in Indiana. Involved in higher level planning, grant writing and research protocol development for other research projects supported by the Center. Assisted in the development of a manual on remote sensing and other technical procedures.
August 1994- Dec. 1994; February- April, 1996	Visiting Researcher, **Institute of Agriculture and Animal Sciences, Tribhuvan University**, Rampur, Chitwan, Nepal. Established a PC-based Geographic Information System (GIS) Laboratory for the Institute and trained Institute faculty. Conducted various research projects integrating GIS, Global Positioning Systems (GPS), spatial statistics and institutional analysis studying forest use and irrigation system management.
Sept 1992- June 1996	Research Assistant, **Workshop in Political Theory and Policy Analysis, Indiana University**. Geographic Information Systems (GIS) Project Leader. Member of the International Forest Resources and Institutions (IFRI) research program. Primary responsibilities include the development of a Foxpro relational database used world-wide for data collection of IFRI projects and participation in the development of survey instrument and participation in grant writing. Programmed approximately 30,000 lines of database code.
Sept. 1989- May 1991	Research Associate, **Technology and Information Policy Program, Syracuse University**. Trained and supervised a research team on survey techniques using expert systems technology. Conducted statistical analyses and authored working papers.

TEACHING EXPERIENCE

	Outstanding Associate Instructor Award. School of Public and Environmental Affairs, Indiana University, Bloomington. April 22, 1997.
Instructor	**School of Public and Environmental Affairs, Indiana University, Bloomington** Information Technology (V501) Fall 1996, 1997. Developed this new module as a part of a revamped MPA curriculum. Designed course material to integrate with material students were to learn in their three core courses (public management, economics and statistics). Integration required significant effort on my part to work successfully with nine other SPEA faculty members each with their own teaching agenda. It was an honor being asked to teach this course (twice) as it is rare at SPEA to have a PhD student teach graduate level courses.
Instructor	**Maxwell School of Citizenship and Public Affairs, Syracuse, New York** Introduction to Computing, Summer, Fall 1990. Honored to be first masters student ever to teach a course to other masters/PhD students at Maxwell.
Guest Instructor	**Political Science, Indiana University, Bloomington**. Taught several analysis sessions as part of Y773, Research Seminar: International Forestry Resources and Institutions. Spring 1994.
Instructor (One of a team)	**Center for Institutions, Population and Environmental Change,** Summer Institute on Environmental Monitoring and Assessment May-June 1997. Taught sessions on the Internet and Global Positioning Systems

to visiting faculty and Ph.D. students.

Instructor — **IBM Corporation, General Technology Division, East Fishkill, NY**
Introduction to VM/CMS, Various classes on mainframe software packages

NON-ACADEMIC EXPERIENCE

June 1991- August 1992 — Research Associate, **Project Performance Corporation, Sterling Virginia.** Consultant to the United States Department of Energy in their Environmental Restoration Program. Designed and developed a PC relational database for the collection and analysis of all restoration projects nation-wide. Primary author of their information system strategic plan.

April 1988- August 1989 — Department leader, Staff programmer, **IBM Corporate Headquarters, Southbury, Connecticut.** Led a team of 17 programmers in the development of a complex electronic forms system that was then distributed for use at many IBM locations in the United States.

June 1984- March 1988 — Senior Associate Programmer, **IBM General Technology Division, East Fishkill, New York.** Designed, developed and maintained numerous complex purchasing information systems.

TECHNICAL SKILLS

Vector GIS software: ESRI Arc-Info, Arc-view
Raster GIS software: Idrissi, Erdas Imagine, Multispec, ENVI
Database development and programming: Microsoft Foxpro, Access
Statistical software: Gauss, Stata, Sas, SPSS, Data Desk
Spreadsheets: Microsoft Excel, Quatro Pro
Internet: FTP, Telnet, Netscape Navigator Gold
Presentation/Graphics: Microsoft Powerpoint, Photoshop, Paintshop Pro
Office Suites: Corel 7.0, MS Office 97
Operating Systems: Windows NT, 95 and 3.11, Unix, DOS, VM/CMS
Global Positioning Systems (field unit and basestation): Trimble, Magellan and Garmin equipment

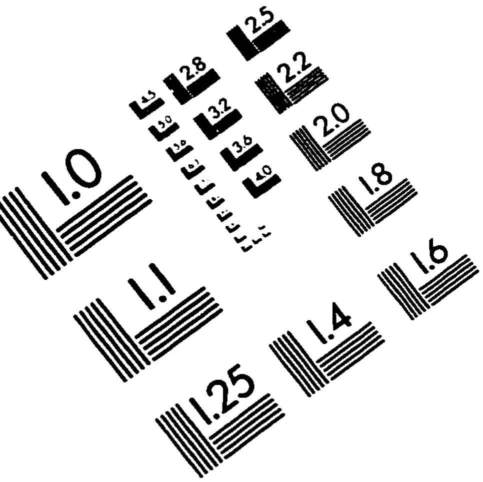
DISSERTATION COMMITTEE

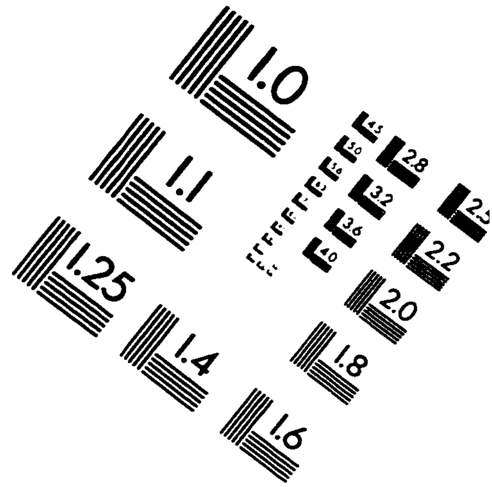
Dr. Elinor Ostrom	Arthur F. Bentley Professor of Political Science, Co-Director, Center for Institutions, Population and Environmental Change and Co-Director, Workshop in Political Theory and Policy Analysis. 513 North Park Indiana University, Bloomington, Indiana 47405 Tel: 812-855-0441 Fax: 812-855-3150 Internet: ostrom@indiana.edu
Dr. J.C. Randolph	Professor and Director of the National Institute for Global Environmental Change, Midwestern Center. School of Public and Environmental Affairs Indiana University, Bloomington, Indiana 47408 Tel: 812-855-4953 Fax: 812-855-7547 Internet: randolph@indiana.edu
Dr. Rosemary O'Leary	Professor School of Public and Environmental Affairs Indiana University, Bloomington, Indiana 47408 Tel: 812-855-0193 Fax: 812-855-7802 Internet: olearyr@indiana.edu
Dr. John T. Williams	Associate Professor Department of Political Science Indiana University, Bloomington, Indiana 47405 Tel: 812-855-5098 Fax: 812-855-2027 Internet: jotwilli@indiana.edu

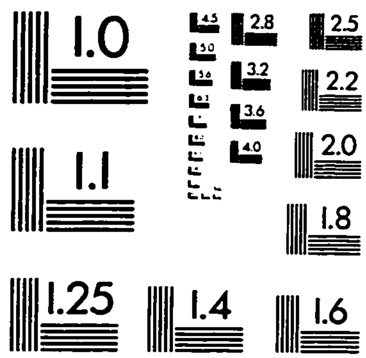
Teaching References

Dr. Barry Rubin	Professor, Associate Dean School of Public and Environmental Affairs Indiana University, Bloomington, Indiana 47405 Tel: 812-855-5058 Internet: rubin@indiana.edu
Dr. Kurt Zorn	Professor School of Public and Environmental Affairs Indiana University, Bloomington, Indiana 47405 Tel: 812-855-9485 Internet: zorn@indiana.edu

IMAGE EVALUATION TEST TARGET (QA-3)

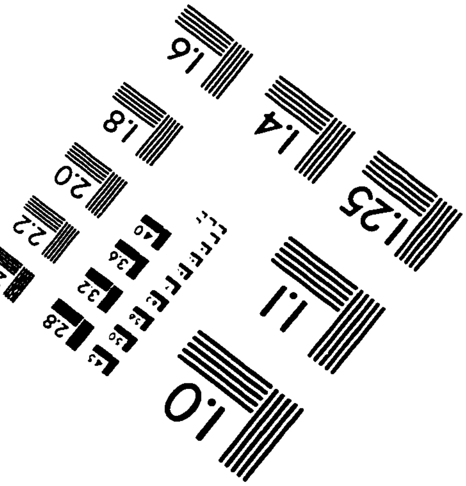


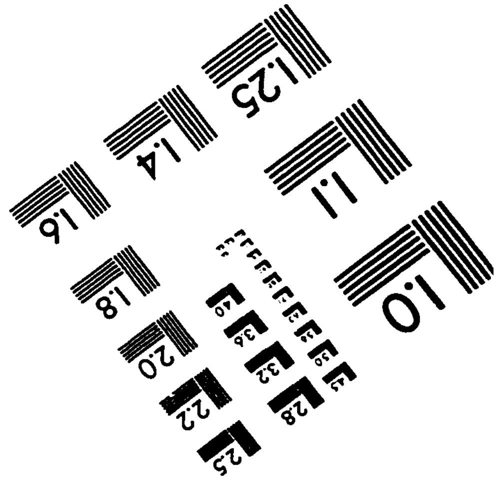




150mm

6″





APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989