GLOBAL ENVIRONMENTAL CHANGE: WHAT ARE THE IMPACTS OF CLIMATE CHANGE AND LAND COVER CHANGE ON DIFFERENT ECOSYSTEMS?

Jane Southworth

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P.O. Box 1346
Ann Arbor, MI 48106-1346

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

JC Randolph

Chair: Dr. J.C. Randolph, Ph.D.

Second Reader: Dr. Otto Doering, Ph.D.

Third Reader: Dr. Vicky Meretsky, Ph.D.

Elinor Ostrom

Fourth Reader: Dr. Elinor Ostrom, Ph.D.

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This dissertation is dedicated to my husband Michael Ryan Kohlhaas

CONTENTS

Abstract

The overall objective of this research is to understand more fully the processes and potential impacts of land cover change and future climate change on both managed and natural terrestrial ecosystems. These changes in land cover are due to human impacts such as deforestation and reforestation (Honduras and Mexico), and also are due to climate change impacts as modeled for 2050 (Midwestern United States).

The potential impacts of future climate change, for the 2050s, across the Midwestern United States, are for decreased maize yields across the southern portions of the study area, and increased yields across the northern areas. The high summer maximum temperatures inhibit maize growth above temperatures of 35 °C, which become more frequent across southern areas of the study region. In addition, increases in climate variability result in decreases in maize yields. In addition, CO_2 fertilization for maize, a C_4 crop, is limited. For forested regions, potential climate change under a doubled CO_2 climate results in an overall shift in forest composition from a transitional oak-hickory and beech-maple composition to a predominantly oak-hickory forest. In addition northern conifers and northern deciduous species were almost completely extirpated from the study region.

Land cover changes, specifically of forest cover, across the study region of western Honduras and eastern Guatemala, show an overall trend of deforestation between 1987 and 1996. However, at the smaller study area scale of La Campa, reforestation is the dominant trend. These differences relate to a ban on logging within the community, land tenure and agricultural intensification processes currently occurring in the region. Research on changes in land cover using different techniques, specifically thermal band

analysis, for Yucatan, Mexico, reveals an improved method of analysis. Using discriminant analysis, it was found that land cover was significantly related to surface temperatures, and as such this provides for a potential method for determining land cover. In addition, the data derived for the land cover analysis can also be used for climate modeling of terrestrial ecosystems, and to link the terrestrial and atmospheric components of the Earth system.

Chapter 1:

Dissertation Introduction & Problem Statement

A. Introduction

The United States Global Change Research Program (USGCRP) has recently produced a publication entitled "Global Environmental Change: Research Pathways for the Next Decade," (USGCRP, 1998) which addresses the upcoming challenges to, and direction for, scientific research in this new millennium. In this discussion of future research needs and challenges, much attention is paid to the issues of climate change and human induced land-cover change, both in terms of causes, rates, and implications. These issues are raised as prominent research areas in the new millennium, and areas where there is a need for greater monitoring, modeling, and understanding of the processes at work.

Human activities across the globe are producing both direct and indirect effects on the global environment. Direct effects include the changing of the landscape due to changes in land cover. Among the indirect effects is the release of gaseous emissions which act to warm the planet. These phenomena are also linked with changes in land cover impacting the local and regional climates both through a change in the local energy balance and through burning of the existing vegetation or removal of the carbon storage. As such, the understanding of the processes and implications of changes in land cover and atmospheric composition is essential.

Global change is occurring at a rapid rate and will affect many different areas of our planet both now and in the future. Land-cover changes in tropical countries can affect the global, regional, and local climates and must be monitored, measured, and understood. Changes in the climate system will affect agricultural and forest ecosystems. Potential future changes can be modeled so as to identify possible alterations in the natural and human systems, and create potential adaptation strategies. If we are to limit the potential impacts from land cover change and future climate changes on our global environment, we must fully understand these processes. The goal of this research is to add to our understanding.

The research presented here is divided into several topics, which, while interconnected within the theme of global change, also have separate research questions associated with them. The thesis can be split into two main sections. The first section of the dissertation deals with climate change impacts on both managed and natural terrestrial ecosystems and is found in Chapters Two to Four. Chapters Two and Three address these issues for agricultural systems and Chapter Four for forested ecosystems, all in the Midwestern United States (Figure 1). The second part of the dissertation deals with land cover change processes and is found in Chapters Five and Six. These chapters address forested ecosystem in terms of land cover changes, predominantly the rates of change in forest cover. Chapter Five addresses these issues for Honduras and Guatemala (Figure 1) where reforestation is the dominant trend within Honduras and deforestation is dominant at the image scale (which includes Guatemala and Honduras). Causes for these differences are discussed. Chapter Six looks at methods for better monitoring land cover change using all seven Landsat TM bands within this analysis. This method also links land cover processes and climate processes via the use of the thermal band for measuring change. Finally in Chapter Seven, conclusions are given to this research and discussion on the implications of this work for environmental science is undertaken. Specific research problems and the questions to be addressed by this research document are now discussed.

B. 1. Climate change

Climate is changing. Based on climate records, the mean global surface temperature has increased approximately 1 °F over the last 100 years and is expected to increase an additional 2-9 °F over the next 100 years (IPCC 1990, 1995). Changes in climate will have implications for climate-sensitive systems such as agriculture and forest ecosystems. The monitoring of these ecosystems, both under current and future climate, is therefore essential to understand the processes of growth and change. In addition, this monitoring can play a key role in the development of adaptation strategies to mitigate these effects in the future.

The changes in atmospheric composition, primarily due to the burning of fossil fuels and changes in land cover, alter the current radiative balance on our planet and act to warm the atmosphere. Such changes are projected to lead to regional and global changes in climate variables such as precipitation, temperature, evaporation, and soil moisture. The rate and magnitude of these changes in climate will vary over time and space but will have very important implications for such sectors as agriculture and forestry, especially in the Midwestern United States, where such land-use dominates.

B. 1. i. Climate change and agriculture

With respect to agriculture, changes in solar radiation, temperature, and precipitation will produce changes in crop yields, crop mix, cropping systems, scheduling of field operations, grain moisture content at harvest, and hence, the economics of agriculture including changes in farm profitability. This research addresses these changes for ten representative agricultural areas across the Midwestern Great Lakes region, a five-state area including: Indiana, Illinois, Ohio, Michigan, and Wisconsin. This region is one of the most productive and important agricultural regions in the world, with over 61% of the land use devoted to agriculture.

Individual crop growth processes are affected differently by climate change. A seasonal rise in temperature will increase the developmental rate of the crop, resulting in an earlier harvest. Heat stress may result in negative effects on crop production. Conversely, increased rainfall in drier areas may result in higher yields. Properly validated crop simulation models can be used to combine the environmental effects on crop physiological processes and to evaluate the consequences of such influences.

The variability of the climate, under current and future climate scenarios, is a critical factor. The consequences of changes in variability may be as important as those that arise due to variations in mean climatic variables (Hulme et al., 1999; Carnell and Senior, 1998; Semenov and Barrow, 1997; Liang et al., 1995; Rind, 1991; Mearns et al., 1984). Most studies of climate change impacts on agriculture have analyzed effects of mean changes of climatic variables on crop production, impacts of changes in climate variability have been much less studied (Mearns et al., 1997; Mearns, 1995).

Within more recent historical records, there have been significant periods of climatic fluctuations such as the dustbowl conditions of the 1930s in the United States, when the dramatically negative effects of climate variability on agriculture were realized. Katz and Brown (1992) showed that for a given climate variable a change in the variance has a larger effect on agricultural cropping systems than does a change in the mean. The effect of possible changes in climatic variability remains a significant uncertainty that deserves additional attention within integrated climate change assessments (Barrows et al., 1996; Mearns et al., 1996; Semenov et al., 1996). The study of economic effects of climate change on agriculture is particularly important because agriculture is among the more climate sensitive sectors (Kane et al., 1992).

Agricultural systems are managed systems and farmers always have a number of possible adaptations or options open to them. These adaptation strategies may potentially lessen future yield losses from climate change or may improve yields in regions where beneficial climate changes occur (Kaiser et al., 1995). Thus, agricultural production responds both to physiological changes in crops due to climate change and also to changes in agricultural management practices, crop prices, costs and availability of inputs, and government policies (Adams et al., 1999).

The primary objective of this research is to identify the potential impacts of climate change and changing climate variability on agriculture in the Midwestern region of the United States. Chapter Two describes in detail the methods used and the climate scenarios created for this analysis. Chapter Three applies these models and techniques to the growth of maize at ten site-specific locations and addresses the following questions:

1. How sensitive are current maize growing agricultural systems to different scenarios of future climate change?
2. What are the additional impacts on site-specific maize growth relating to changing climate variability?
3. Which areas gain and which areas lose under these future climate scenarios?
4. What are some potential adaptation strategies for this region?

B. 1. ii. Climate change and forests

Global climate change is expected to affect the growth and distribution of forests at several spatial and temporal scales (Graham et al., 1990; Randolph and Lee, 1994; Loehle and LeBlanc, 1996; Schenk, 1996; Lindner et al., 1997). Although some of the most adverse impacts of future climate change are projected to occur in the Midwest and Great Plains regions (Loehle and LeBlanc, 1996), few studies have focused on these areas.

Tree species respond to climate change in an individualistic manner. Paleoecological studies of Holocene forests reveal that forest communities do not respond as units (Webb, 1987; Davis, 1981; Huntley, 1991). Instead, new species assemblages form and reform as each species responds to climate change. Characteristics such as competitive ability and seed dispersal mechanisms are critical to determining regional shifts in dominance (Davis, 1986; Webb, 1986; Malanson, 1993), particularly when climate change is studied on time scales of 10,000 years or less (Solomon et al., 1981; Solomon and Webb, 1985). Adjustment to a new physical environment depends upon the environmental tolerance ranges of the species. Species may flourish under the new climatic conditions, migrate into a new region, or be extripated in a given region (Randolph and Lee, 1994). Such individualistic responses necessitate a species based model for study and analysis.

The JABOWA-II forest growth model was used to provide species-specific responses to site conditions (*e.g.*, climatic, edaphic) while respecting competition for limited resources (*e.g.*, light, nutrients, water). Forest growth was simulated annually from 1981 to 2060 for every 4-km^2 area in the region having 30% or more forest cover.

Chapter Four discusses this research in which tree species response to a doubled CO_2 climate was simulated on a relatively broad spatial scale: the three-state region of Ohio, Indiana, and Illinois. The temporal scale (80 years) was constrained by the point in time (2060) at which the effects of doubled atmospheric CO_2 are expected to be fully realized (Smith and Tirpak, 1989). This study uses the Oregon State University (OSU) climate model for a doubled CO_2 equilibrium run, which produces similar results to both the Canadian and Hadley center general circulation model transient runs for the same time period (Doherty and Mearns, 1999).

The overall objective of this study was to examine the possible transient responses of tree species of the Southern Great Lakes Region to a 2x CO_2-changed climate scenario. Specific questions addressed in Chapter Four are:

1. How will the changed climate scenario affect total basal area of each tree species studied and how will this vary across the study area?
2. How will the resultant regional population centers of the tree species respond to the changed climate?
3. Which species will thrive, which will die out, and how will this vary spatially?
4. What will the likely forest assemblages be in 2080 for this study area and where will the main shifts in forest type occur?
5. What are the implications for these changes when considering current land use in this region and the likelihood of such future changes in forests?

B. 2. Land-cover change and forest loss

Gaining a better understanding of the ways that land cover and land use practices evolve is a primary concern for the global change research community. Changes in land cover impacts climate, as well as the diversity and abundance of terrestrial ecosystems. Hence, the ability to project future states of land cover is a requirement for making numerical predictions about other global changes, because anthropogenic causes drives land-cover change (Turner et. al., 1993). Many see tropical deforestation as a potential threat to ecological sustainability and socioeconomic development for many regions of the world. The extent of forest cover affects many important global systems, such as the carbon budget, the climate system, and the hydrological system. Knowledge of the areal extent of forest cover and its changes is therefore an essential step in many global change studies, and in many areas of the globe these are still relatively unknown.

Changes in forest cover in tropical countries generally illustrate increasing rates of deforestation as we enter the twenty-first century. Hence, it is imperative that we understand the patterns and processes behind such changes, as well as monitoring the change rates, in order to evaluate whether these are long-term trends or simply anomalies. In addition, this will enable us to address the implications of such changes (Fujisaka et al., 1996; Houghton et al., 1991).

The research presented in Chapter Five addresses major issues in the use of remotely sensed data and the importance of considering a range of biophysical, political and social factors when addressing change. Many studies continue to focus at the national level, often due to limited data sources, and political decision-making on a countrywide basis. Therefore this has important implications for policy makers and economic development initiatives, particularly for environmental issues. It is becoming more important to interpret relationships and linkages between local, regional and national levels of analysis. Moreover, understanding such linkages requires the integration of social data.

Honduras makes an interesting region of study because national level statistics indicate that Honduras is experiencing deforestation at a national level (FAO, 1999). At the sub-national level, however, notable variations exist in agricultural activities, institutional arrangements, processes of economic development, and social change. These are critical factors causing change in forest cover. Our focus area of La Campa, Honduras is of specific interest because of changing institutions for forest management in addition to the experience of nationwide changes in agricultural technologies. La Campa has made particular efforts to conserve its forests, including the prohibition of logging. These issues will be addressed in the discussion with specific reference to the role of local institutions.

The main objective of the research is to identify areas of deforestation or reforestation within the study area and to address the potential impacts of such changes on land cover in the western Honduras study area (Figure 1). Specific questions addressed in this research are:

1. What are the amounts of deforestation and reforestation occurring across the study area?
2. What are the dominant causes of these changes in land cover and the implications of such changes for the focus region?
3. How do the patterns of accessibility vary spatially across the region, and how do these relate to forest change?
4. How does land-tenure impact forest cover within La Campa?

B. 3. Improved techniques for monitoring land cover

One of the most important land-surface parameters is the land-surface temperature (Wittich, 1997; Sobrino et al., 1991). The major advantages of using Landsat TM band 6 thermal data, as is proposed in this research, is that this information, when converted into temperature values, can be used to link directly to other science fields, (e.g., micrometeorology). Land surface processes are of paramount importance for the re-distribution of energy and moisture between the land and the atmosphere. Surface temperature is an important parameter in the characterization of energy exchange between the ground surface and the atmosphere. Landsat TM thermal band data can be used for this purpose (Hurtado et al., 1996). These exchanges of radiative, moisture, and heat fluxes affect biosphere development and the physical living conditions at the Earth's surface (Bastiaanssen et al., 1998; Hall et al., 1991). Spatial variations in land cover, soils, and moisture are very important for studied a multitude of processes. However, the spatial variability of meteorological conditions cannot always be obtained from a limited number of climate stations. In such instances, remote sensing data provide an excellent means of obtaining consistent and frequent observations of spectral reflectance and emittance of radiation of the land surface on a micro to macro scale. As such, remote sensing provides an instantaneous snapshot of the radiative properties of the particular land surface (Bastiaanssen et al., 1998). In addition, the thermal band, like vegetation indices, allows for a continuous representation of land cover, rather than the creation of discrete land cover classes such as in classification techniques (Lambin, 1999).

The research presented in Chapter Six investigates the utility of integrating Landsat band 6 thermal data for land cover classification and, specifically, for the differentiation between successional stages of forest growth. Such successful differentiation has become critical for the assessment of land cover and land use changes after deforestation or clearing. The ability to monitor and measure changes in land cover within these areas of deforestation or clearing is critical to addressing questions concerning changing climate and other issues pertaining to deforestation in many tropical regions. The study area of this research is within the state of Yucatan, Mexico (Figure 1), which is a region of tropical dry forest. Tropical dry forests cover more area than humid tropical forests, yet there have been few studies of their structure, functions, and processes even though they are greatly affected by human activities. Given the locations of many tropical dry forest regions, these areas will be increasingly affected in the future due to global and regional socioeconomic and political pressures.

The overall objective of this research is to integrate thermal band imagery analysis into vegetation land cover analysis methodologies and to assess the impacts of including such data within traditional analysis techniques. Specific research questions addressed in Chapter Six are:

1. How effective is the thermal band information for vegetation studies of successional change?
2. What additional information is provided by thermal band information when it is included in vegetation studies?
3. How can the use of the thermal band information be incorporated into studies which currently use only data from the reflective bands?

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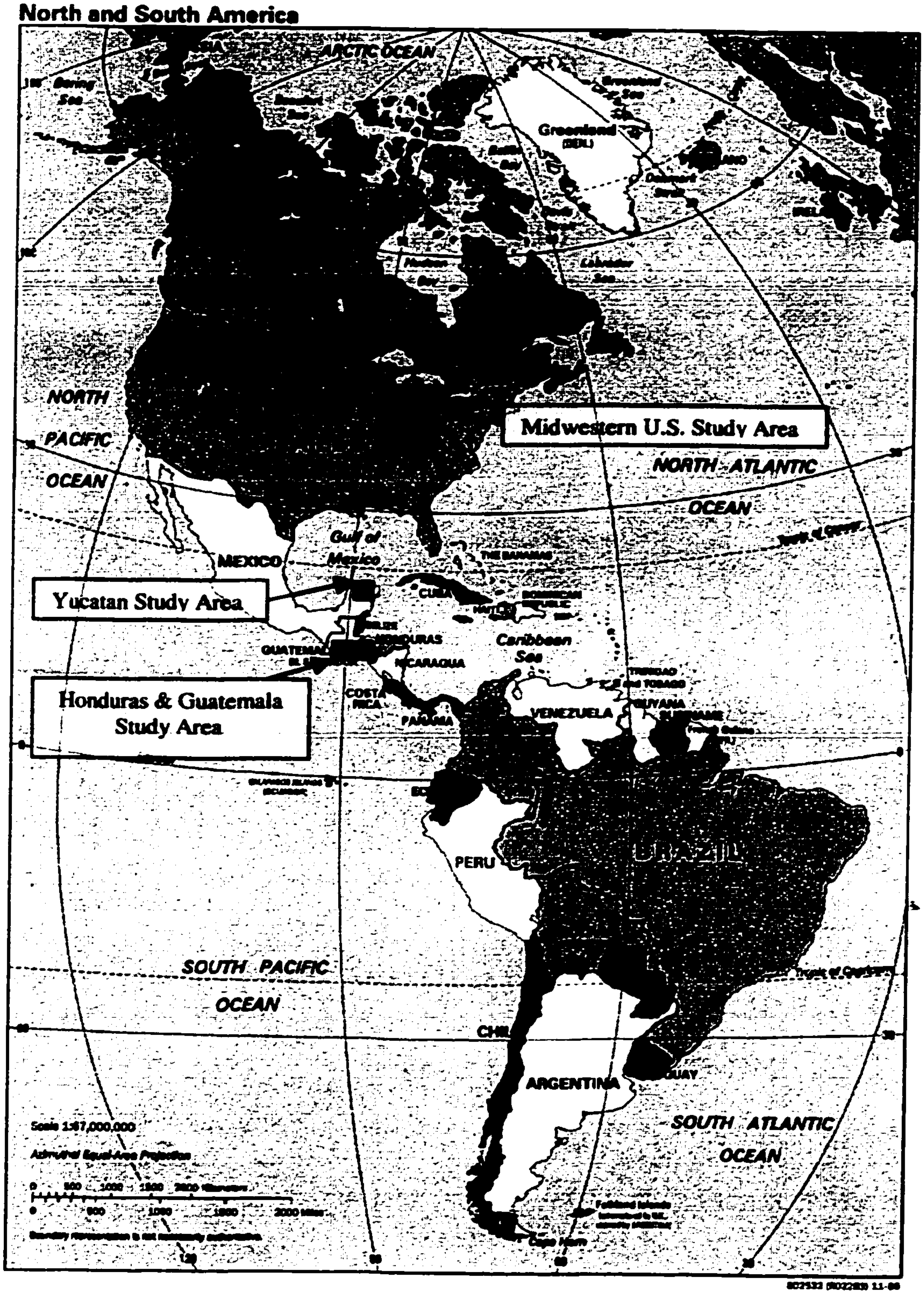
Figure 1: Research Sites



Chapter 2:

Issues and Approaches to Climate Change Concerns for Climate Modeling in the Upper Midwest

Book Chapter draft from:
"EFFECTS OF CLIMATE CHANGE AND CLIMATE VARIABILITY
ON THE AGRICULTURAL PRODUCTION SYSTEM" Kluwer Academic
Publishers, 2001.

A. ABSTRACT

Any change in climate will have implications for climate-sensitive systems such as forestry, other natural resources, and agriculture. With respect to agriculture, changes in precipitation, temperature, and solar radiation will produce changes in crop yields, scheduling of field operations, and grain moisture content at harvest. Climate change will also have a host of effects on the economics of agriculture, including changes in prices, farm profitability, trade, and regional or national comparative advantage. The impacts of climate change will depend on: (1) the magnitude of the change in climate, and (2) how well agriculture can adapt to these changes (Kaiser et al., 1995).

Farming practices are weather dependent, and yields from a single farm vary significantly from year to year depending on each season's weather. We may expect, therefore, that even small changes in climate will have an impact on agriculture. Warmer, wetter winters may cause delays to spring sowings, more over-wintering of pests and diseases and faster developments of winter-sown cereals, leaving them vulnerable to spring frosts. More variability in weather may lead to a greater frequency

of hot, dry summers requiring irrigation for many crops, or more wet summers causing delay to maturity in cereals (Peiris et al., 1996).

Individual crop growth processes are affected differently by climate change. A rise in temperature may increase the developmental rate of the crop, thus shortening the growing season, and resulting in a negative effect on crop production. Conversely, increased rainfall in drier areas may reduce the effect of water limitation on crop photosynthesis, and result in increased yields. Properly validated crop simulation models combine the environmental effects on many crop physiological processes, and can be used to evaluate the consequences of such competing influences (Peiris et al., 1996).

The formation of climate change scenarios that incorporate changes in variability can provide clarification regarding an aspect of uncertainty in climate change impacts assessment that has been heretofore ignored (Mearns, 1995).

B. INTRODUCTION

Understanding the climate system is a problem of great intrinsic scientific interest. Our growing understanding of interactions between the atmosphere, oceans, biosphere, cryosphere and land surface is revolutionizing the Earth sciences. Moreover, in recent years, a sense of urgency has infused research on modeling the climate system. The prospect of human activities altering atmospheric composition, affecting climate globally and regionally, and ultimately affecting human economies and natural ecosystems, has stimulated the development of models of the climate system (IPCC, 1990).

Interest in the impact of CO_2 and its role in influencing climate change can be traced as far back as 1827, although it is more common to attribute the origins of CO_2 impacts research to the work of Arrhenius in 1896 and Chamberlain in 1897 (Chiotti and Johnston, 1995). Almost a century later, concern over climatic change has reached global dimensions, and concerted international and cooperative efforts have been initiated in recent years to address this problem. Although there continues to be considerable debate regarding the causes of climate change, either induced by anthropogenic activities or simply falling within a normal range of natural variability, there is a general consensus regarding future climates and the potential implications for agriculture. In terms of agriculture, climate change and changing climate variability is predicted to have a significant impact, especially the combined effects of elevated temperatures, increased likelihood of droughts, and reduced crop-water availability (Chiotti and Johnston, 1995).

Human activities (primarily the burning of fossil fuels and changes in land use and land cover) are apparently increasing the atmospheric concentrations of greenhouse gases, which alter radiative balances and tend to warm the atmosphere. These changes in greenhouse gases are projected to lead to regional and global changes in temperature, precipitation, and other climate variables. In turn this is expected to result in global changes in soil moisture, an increase in global mean sea level, and prospects for more severe extreme high-temperature events, floods, and droughts in some places (IPCC 1990).

Average global temperatures at the planet's surface are rising based on climate records. The five warmest years since global records began in the mid-19th century, have all occurred in the 1990s, and ten of the eleven warmest have been since 1980 (Pearce, 1997).

Based on a range of sensitivities of climate to changes in the atmospheric concentrations of greenhouse gases (IPCC, 1995), climate models project that the mean annual global surface temperature will increase by 1-3.5 °C by 2100. In addition, that global mean sea level will rise by 15-95 cm, and change in the spatial and temporal patterns of precipitation will occur (IPCC 1990, 1995).

Studies show that human health, ecological systems, and socioeconomic sectors (e.g., hydrology and water resources, agricultural production, coastal systems, and human settlements), which are vital to sustainable development, are sensitive to both the magnitude and rate of climate change, as well as to changes in climate variability. Whereas many regions are likely to experience adverse effects of climate change, some effects of climate change are likely to be beneficial. Climate change represents an important additional stress on those systems already affected by increasing resource demands, unsustainable management practices, and pollution, which in many cases may be equal to or greater than the stresses of climate change (IPCC, 1990; 1995).

Climate change also will take place in the context of economic development, which may make some groups or countries less vulnerable to climate change (for example, by increasing the resources available for adaptation). However, those countries that experience low rates of growth, rapid increases in population, or ecological degradation may actually become increasingly vulnerable to potential changes (IPCC, 1990).

Changes in climate will interact with stresses that result from actions to increase agricultural production, affecting crop yields and productivity in different ways, depending on the types of agricultural practices and systems in place. The study of economic effects of climate change on agriculture is particularly important because agriculture is among the more climate sensitive sectors (Kane et al., 1992). The main direct effects will be through changes in factors such as temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development. Also there will be effects due to changes in atmospheric CO_2 concentration (which may have a beneficial effect on the growth of some crop types).

Indirect effects will include potentially detrimental changes in diseases, pests, and weeds, the effects of which have not yet been quantified in most available studies. Evidence continues to support the findings of the IPCC SAR that "global agricultural production could be maintained relative to baseline production" for a growing population under 2x CO_2 equilibrium climate conditions (Mitchell et al., 1995; Peiris et al., 1996; Adams et. al., 1999). In middle and high latitudes, global warming will extend the length of the potential growing season allowing earlier planting of crops in the spring, earlier maturation and harvesting, and the possibility of completing two or more cropping cycles during the same season. Agriculture of any kind is strongly influenced by the availability of water. Climate change will modify rainfall, evaporation, runoff, and soil moisture storage. Changes in total seasonal precipitation or in its pattern of variability are both important. The occurrence of moisture stress during flowering, pollination, and grain filling is harmful to most crops and particularly so to corn, soybeans, and wheat. Increased evaporation from the soil and accelerated transpiration in the plants themselves will cause moisture stress; as a result there will be a need to develop crop varieties with greater drought tolerance (Rosenzweig and Hillel, 1995).

Conditions are more favorable for the proliferation of insect pests in warmer climates. Longer growing seasons will enable insects such as grasshoppers to complete a greater number of reproductive cycles during the spring, summer, and autumn. Warmer winter temperatures may also allow larvae to winter-over in areas where they are now limited by cold, thus causing greater infestation during the following crop season. Altered wind patterns may change the spread of both wind-borne pests and of the bacteria and fungi that are the 'agents' of crop disease. Crop-pest interactions may shift, as the timing of development stages in both hosts and pests is altered (Rosenzweig and Hillel, 1995).

There is extensive discussion concerning the ability of North American agriculture to adapt to changing climatic conditions (Adams et al., 1990; Mearns, 1995; Mearns et al., 1996; Peiris et al., 1996; Adams et al., 1999). Globally crop yields have increased from 1950-2000 regardless of changes in global mean temperatures (Figure 1). Looking at just North America however, it is unknown whether such a trend will continue into the next century, with the likely changes in climate at a much more rapid pace. The productivity of agricultural resources in North America is moderately too highly sensitive to climate change. Most studies, however, have not fully considered the effects of potential changes in climate variability; water availability; stresses from pests, diseases, and fire; or interactions with other existing stresses. Warmer climate scenarios (4-5 °C increases in North America) have yielded estimates of negative impacts in eastern, southeastern, and corn-belt regions and positive effects in northern plains and western regions (IPCC, 1990).

This research addresses the issues of changing mean climatic conditions and changes in the variability of climate around this mean. The occurrence and frequency of extreme events may become of increasing importance. The study area for this research is the Midwestern United States. Crops to be modeled are three types of corn, three types of soybeans, and one variety of wheat, in terms of their current and future yields. In order to study this region spatially 10 representative farms have been selected (Figure 2) based on the ecoregions of this area (Figure 3). Each ecoregion has a representative farm within it. Crop yields will be evaluated using the crop model DSSAT under current and future climate conditions at each representative farm location, for all crop types.

C. THE CLIMATE SYSTEM

C.1. Background on the climate system

The components of the climate system which are important for climate change (the atmosphere, oceans, terrestrial biosphere, glaciers, ice sheets, and land surfaces) influence global and regional climate in a number of distinct ways: (a) by influencing the composition of the Earth's atmosphere, thereby modulating the absorption and transmission of solar energy and the emission of infrared energy back to space; (b) through alterations in surface properties and in the amount and nature of cloud cover, which have both regional and global effects on climate; and (c) by redistributing heat horizontally and vertically from one region to another through atmospheric motions and ocean currents (IPCC, 1990; 1995). In the natural state, the various flows between the climate system components are usually very close to being exactly balanced when averaged over periods of one to several decades. For example, prior to the industrial revolution, the uptake of CO_2 by photosynthesis was almost exactly balanced by its release through decay of plant and soil matter, as evidenced by the near constancy of the atmospheric CO_2 concentration for several millennia prior to about 1800. However, from one year to the next there can be modest imbalances that fluctuate in sign, due to the natural variability of the climate system. Humans are affecting the operation of climate processes, and hence, the natural balance of the climate system, through persistent regional to global scale alterations in the composition of the Earth's atmosphere and in the properties of the land surface (IPCC, 1995).

C.1.1 Radiative forcing

Anthropogenic greenhouse gases and aerosols affect the climate system by altering the balance between absorbed solar radiation and emitted infrared radiation.

The imbalance is quantified as the "radiative forcing", which is defined as the change in net downward radiation (combined solar and infrared) at the troposphere. The surface climate responds to the initial change in net radiation at the troposphere rather than at the surface itself or at the top of the atmosphere because the surface and troposphere are tightly coupled through heat exchanges, and respond as a unit to the combined heating perturbation. The adjustment of the stratosphere is included in the radiative forcing because the stratosphere responds quickly and independently from the surface-troposphere system. Non-anthropogenic radiative forcing relevant at the decade to century time-scales include variations in solar luminosity and volcanic eruptions, the latter producing reflective sulfate aerosols which are effective for several years if injected into the stratosphere (IPCC, 1990).

C.1.2 Feedbacks

A feedback is a process whereby an initial change in some variable ("A") leads to a change in another variable ("B") which then produces further changes in the initial variable. A positive feedback is such that the change in B leads to further changes in A in the same direction as the original change, thereby tending to amplify the initial change. A negative feedback, on the other hand, acts to diminish the initial change. Among the feedback's which have to be considered in the calculation of global mean climatic change are the following: (*a*) *Water vapor amount:* in a warmer climate the atmospheric concentration of water vapor will increase. Since water vapor is a greenhouse gas, this represents a positive feedback; (*b*) *Clouds*: changes in clouds are difficult to calculate reliably but clouds have a strong radiative effect, and are, therefore, likely to produce a noticeable feedback. This feedback depends on changes in the amount, altitude and characteristics of the clouds, as well as on the reflectivity of the underlying surface, so even the sign of the feedback is uncertain; (*c*) ***Areal extent of ice and snow***: a reduction in the area of sea ice and seasonal snow cover on land as climate warms will reduce the surface reflectivity, thereby tending to produce greater warming (a positive feed-back), however, concurrent changes in cloud cover complicate the picture considerably; (*d*) ***Vegetation*** : changes in the distribution of different biomes or in the nature of vegetation within a given biome can also lead to changes in the surface reflectivity, thereby exerting a feedback effect on climatic change; (*e*) ***The carbon cycle:*** the effect of climate on the terrestrial biosphere and the oceans is likely to alter the sources and sinks of CO_2 and CH_4, leading to changes in their atmospheric concentrations and hence causing a radiative feedback (IPCC, 1990; 1995).

C.2. Climate Modeling

The major components of the climate system that are important for climate change and its consequences, such as sea level rise, during the next century are: the atmosphere, oceans, terrestrial biosphere, glaciers and ice sheets, and land surface. In order to project the impact of human perturbation on the climate system, it is necessary to calculate the effects of all the key processes operating in these climate system components and the interactions between them. These climate processes can be represented in mathematical terms based on physical laws such as the conservation of mass, momentum, and energy. However, the complexity of the system means that the calculations from these mathematical equations can be performed in practice only by using a computer. The mathematical formulation is therefore implemented in a computer program known as a 'model' (IPCC, 1990; 1995).

The climate system can be represented by models of varying complexity, i.e., for any one component of the climate system a hierarchy of models can be identified. The main differences between models within a given hierarchy are:

- the number of spatial dimensions in the model,
- the extent to which physical processes are explicitly represented,
- the level at which empirical parameterizations are involved, and
- the computational cost of running the model.

Computer-run, mathematical simulations or models of the atmosphere and ocean are the principal tools for predicting the response of the climate to increases in greenhouse gases. The most sophisticated of these are called general circulation models, or GCMs. These models solve the equations of the atmosphere and oceans approximately, by breaking their domains up into volumetric grids, or boxes, of which each is assigned an average value for properties like velocity, temperature, and humidity. The size of the box is the model's spatial resolution. The smaller the box the higher the resolution. An assumption of research involving such models is that the realism of climate simulations will improve as the resolution increases (IPCC, 1990). GCMs include the interaction of the atmosphere with the oceans and with the surface of the Earth, including plants and other ground cover.

The great power of mathematical models lies in their ability to simulate the behavior of systems, such as the atmosphere, that are too complex or extensive for simple, intuitive reasoning. The key is to incorporate the best possible representation of all the important processes and feedback's necessary to characterize the climate system, while keeping within the practical capabilities of modern computers. They allow us to test by mathematical simulation what should happen to climate in response to a wide variety of changes. The purpose of these GCMs is to describe how major changes in the earth's atmosphere, such as changes in the levels of CO_2 in the atmosphere, would affect the pattern of climate around the globe, and more specifically how would such changes be manifest in terms of such meteorological variables as temperature, precipitation, sea ice, cloud cover, winds etc. GCMs, while useful for climate change studies, are not intended to predict weather patterns (i.e., passage of frontal systems, likelihood of rain on any given day etc.,). In addition the coarse spatial resolution fails to account for local topographically induced regional climate. They are however very useful tools for examining the long-term climatic trends, the major patterns and the dominant responses of the climate system to significant changes (Adams et al., 1999).

A growing number of GCMs, many with independently derived components, are available for inter-comparison. There is a growing store of meteorological and oceanic observations against which model predictions can be tested. In addition, information on past climate change is available recorded by natural processes in rocks, sediments, and ice cores, that allow us to assess the ability of models to replicate the known features of climates different from that of the present day.

All of the GCM experiments designed to assess the impact of increases of greenhouse gases point to global warming through the coming century, with accompanying changes in rainfall and other meteorological quantities. Still, the complexity of the climate system is a tremendous obstacle to predicting future climate change. Neither climatological observations nor present climate models are sufficient to project how climate will change with certainty. A workable approach is that adopted by the Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP), which is based on projections of the expected growth of greenhouse gases and the combined results of many GCMs (Figure 4).

In terms of mean global surface temperature, the consensus prediction of the IPCC is for an increase in global mean surface temperature of 0.5-2.0 °C by the year 2050, in response to an anticipated increase of 1% per year in CO_2. Moreover, were the amount of CO_2 to double, the consensus forecast is for an eventual warming of 1.5-4.5 °C. Such changes, if realized, would represent a major climatic change, i.e., shifts in species, changes in agricultural crops grown etc.

Predictions of future climate are imperfect because they are limited by uncertainties that stem from:

(1) the natural variability of climate;

(2) our inability to predict accurately future greenhouse-gas and aerosol emissions;

(3) the potential for unpredicted or unrecognized factors to perturb atmospheric conditions; and

(4) our as-yet incomplete understanding of the total climate system.

The reliability of climate-model predictions depends directly upon each of these. In an attempt to improve our modeling understanding and capacity new and improved GCMs are continuously being developed.

The most complex atmosphere and ocean models are the three-dimensional atmospheric general circulation models (AGCMs) and ocean general circulation models (OGCMs), both of which are extensively reviewed in the SAR WGI (Chapter 5). These models divide the atmosphere or ocean into a horizontal grid with a typical resolution of 2-4° latitude by 2-4° longitude (in the latest models), and typically 10 to 20 layers in the vertical. They directly simulate winds, ocean currents, and many other variables and processes characterizing the atmosphere and oceans. Both AGCMs and OGCMs have been used extensively in a stand-alone mode, with prescribed ocean surface temperatures and sea ice in the case of AGCMs and with prescribed surface temperatures and salinity, or the corresponding heat and freshwater fluxes, in the case of OGCMs. An atmosphere ocean general circulation model (AOGCM) consists of an AGCM coupled to an OGCM, with information about the state of the atmosphere and ocean adjacent to, or at the sea surface, used to compute exchanges of heat, moisture and momentum between the two components. AOGCMs compute radiative transfer through the atmosphere (explicitly modeling clouds, water vapor and other atmospheric components), snow and sea ice, surface fluxes, transport of heat and water by the atmosphere and ocean, as well as the uptake of heat by the oceans (which delays and modifies the initial surface temperature response but contributes to sea level rise through expansion of ocean water as it warms). Thus, coupled AOGCMs explicitly compute the fast feedback processes, whose interactive effect determines climate sensitivity. Because of computational constraints, however, the majority of these processes are parameterized to some extent, i.e., the equations used contain constants for many variables even though this simplifies reality. However, in order to accurately calculate every variable we need more information on the climate system and improved computers. Such developments in the models are occurring continuously but there is no single GCM, as of yet, which is superior to all other models, and currently all models do contain some simplified equations or such constants within their programming. More detailed representations are either not practical or have not been developed for use in a global model. Some parameterizations inevitably include constants that have been tuned to observations of the current climate. AOGCMs attempt to explicitly represent a large number of processes, while simpler models represent these processes by a small number of adjustable parameters.

Measurements of past and current levels of CO_2 and other greenhouse gases indicate that we should have already increased the global greenhouse effect by man-made, or anthropogenic additions, by nearly 40% in the last 150 years. If these changes were the only process of importance, then the same mathematical climate models suggest that the average global mean surface temperature should have risen by about 1 °C during this time. Available climate data suggest that the mean global temperature has indeed risen, but unsteadily and by only about half that amount (Karl *et al.*, 1995).

In addition to the increase of greenhouse gases however, we have also changed the composition of the atmosphere in ways that act to cool the surface temperature.

This includes the anthropogenic decrease of stratospheric ozone, and an increase in anthropogenic microscopic sulfate particles, often readily apparent during the warm season as smog. The effect of these additional atmospheric constituents on global climate is less certain than that of the better known greenhouse gases, but models suggest that in some areas they may have already acted to significantly retard greenhouse warming. It is important to note, however, that the global-scale warming predicted in climate modeling experiments from future greenhouse gas increases is substantially larger on a global average than a regional cooling expected from these other sources (Karl *et al.*, 1995).

C.3. Climate Variability

The consequences of changes in climate variability are as important as those that arise due to variations in the mean climate state (Liang et al., 1995). Much of the global warming debate, for instance, focuses on changes in global average air temperature anomalies; however, there is always important inter-annual variability, not necessarily systematic change in air temperatures that has important implications for applied climatological research.

Without knowing what the natural variability of global temperature is (random or not), scientists cannot be sure how much extra temperature change is being caused by humans. To take an imaginary example: if natural year to year variation in global mean temperature were only a tenth of a degree, and the warming from people's activities a whole degree, it would be very easy to detect. On the other hand, if the warming were a tenth of a degree, and natural variation a whole degree, warming from human activities would be very hard to detect. Right now, the magnitude of any suspected human-induced global warming seems to be rather similar to the magnitude of the natural background variation in temperature, making the 'greenhouse signal' somewhat difficult to interpret (Figure 5).

There is considerable quantitative uncertainty concerning how agricultural crops respond to changes in climate variability, although it is known qualitatively that changes in variability can have serious effects. There have been significant periods of climatic fluctuations within the near historical record, such as the dustbowl of the 1930s, when the dramatic and negative effects of climate variability on agriculture were realized. Agricultural vulnerability to such climatic fluctuation will only increase in the future with the increased mean temperatures due to global warming (increased stress onto an area which would make it even less able to adapt to the changes in the climatic variability). Katz and Brown (1992), showed that the change in the variance has a larger effect on changes in agricultural cropping systems due to extremes than does a change in the mean of a given climate variable. The effect of possible changes in climatic variability remains a significant uncertainty that has not received much attention within the integrated climate change assessments (Mearns et al., 1996). This research aims to help change this, as is illustrated in the next chapter (chapter 3). Most climate impact studies rely on changes in means of meteorological variables, such as temperature, to estimate potential climate impacts, including effects on agricultural production. However, extreme meteorological events, say, a short period of abnormally high temperatures, can have a significantly harmful effect on crop growth and final yield. These changes in the probabilities of extreme events need to be taken into consideration in order to obtain realistic estimates of the impact of climate changes such as increases in mean temperature that may arise from increases in atmospheric CO_2 concentrations (Mearns et al., 1984).

A growing consensus regarding the plausibility of increases in mean temperature due to increases in atmospheric CO_2 concentration has galvanized attempts to assess possible impacts of such changes on various spheres of human society (IPCC, 1990; 1995; Rosenburg, 1992; Rosenzweig and Hillel, 1993; Pearce, 1997). Efforts have been made to determine the effect of particular changes in mean temperature on the growing seasons and productivity of individual crops (Peiris et al., 1996, Thornton et al., 1997; Lala et al., 1998; Rosenzweig and Hillel, 1998). Empirical crop-climate models are often used to this end. Most of these studies involve the construction of various climate change scenarios by shifting mean monthly temperatures and/or precipitation amounts (Mearns et. al., 1984).

It is important to keep in mind that the actual growing crop is subjected to temperatures that are continually varying, including daily extremes that are not necessarily well reflected in the mean values. Plants can have highly non-linear responses to short-lived temperature and trends, particularly runs of extremely high temperatures over several consecutive days (Mearns et al., 1984). Because the relationship between changes in mean temperature and associated changes in the probabilities of extreme temperature events is inherently non-linear, reliance on mean temperature changes essentially precludes any consideration of extreme temperature events when performing climate impact analysis. Hence, it is essential to analyze both the impacts of the changing climate scenarios on mean climate conditions and also its affect on climate variability. Mearns (1995) found increasing the variability of climate for a given location in Kansas, resulted in increased yield variability and hence, crop failure. Most of the increases in crop failures were caused by increased soil moisture deficits which resulted in poor grain fill.

While most climate change agricultural studies have analyzed the effects of mean changes of climate variables on crop production, impacts of changes in climate variability have been studied much less. The focus on the effects of mean climate change has provided only limited information on how future climate could affect agriculture. Additional information on changed variability effects is needed to further elucidate uncertainties in our knowledge of possible impacts of climate change (Mearns, 1995). A central research task is to perform sensitivity analyses of crop responses to changed climatic variability to determine the important thresholds of change. In order to separate the crop response to mean changes in climate from its response to variability changes, time series of climate variables with changed variability must be constructed or simulated, and the crop model subjected to a range of variability changes.

Increases in rainfall intensity pose a potential threat to agriculture in the forms of increased nutrient leaching, soil erosion, leaching of chemical and animal wastes. Current climate models of future climates cannot adequately model potential changes in such climate variability and so frequently separate sensitivity analyses of the impacts of such changes in extreme events must also be conducted (Adams et al., 1999).

C.4. Agricultural adaptation strategies

In the United States approximately 400 million acres of farmland are cropped each year which makes up about 20% of the country's total land area. Of this land area nearly 60 million acres (15%) are irrigated, mostly in the arid West and Midwest. The value of American agricultural commodities exceeds $165 billion at the farm level and over $500 billion after processing and marketing. In world markets the United States accounts for more than 25 percent of the total trade in wheat, corn, soybeans, and cotton (USDA, 1997a ; Adams et al., 1999).

Agricultural systems are managed and farmers always have a number of possible adaptations or options open to them. These adaptations include changing planting and harvest dates, rotating crops, selecting different crops or crop varieties for cultivation, irrigation, using fertilizers, and choosing different tillage practices. These adaptation strategies may potentially lessen future yield losses from climate change or may improve yields in regions where beneficial climate changes occur. As farmers make decisions about which crops to grow market price can create further possible adaptation strategies. Thus, agricultural production responds both to biophysical changes in crops due to climate change and also to changes in agricultural management practices, crop prices, the cost and availability of inputs, and government policies. In the future, adaptations may include the introduction and use of new crop varieties that thrive under changed climates (better adapted to high temperatures, increased drought, or late freezes), or investments in irrigation as insurance against decreased and more variable precipitation patterns. The extent of adaptation depends upon many factors including information flow to the farm level, access to capital, and the potential implementation of new government programs and policies (Adams et al., 1999).

D. METHODS

Our modeling efforts used VEMAP data (and NOAA data for verification), and HADCM2 GCM future model data for two scenarios, one for greenhouse gas only, and one for a greenhouse gas and sulfate run.

D.1. VEMAP

The VEMAP dataset includes daily, monthly, and annual climate data for the conterminous U.S. including maximum, minimum, and mean temperature, precipitation, solar radiation, and humidity. The monthly data are used here and these are climatological means. VEMAP data was selected for use in this study due to the representative farms not all being close to a NOAA weather station (i.e., within 100 miles). Hence, it was decided that using the VEMAP dataset, which has been tested for accuracy, had missing data replaced, and interpolated to a half degree by half degree grid would be preferable. The NOAA data and VEMAP data were tested for compatibility and found to be near identical when the station was close by, but had small but significant differences when the station was over 60 miles away (especially due to topographical distances). VEMAP data were also compared to the closest station available to them (usually not a NOAA weather station). In this instance all the VEMAP data and the nearest climate station data for temperature and precipitation data were near identical. It was not possible to use these nearest station data however due to the lack of solar radiation data. Hence, we used the VEMAP data set as our primary source of current climate data.

D.1.1. Temperature and precipitation records

First, VEMAP creators generated one year of daily precipitation and maximum and minimum temperature for each VEMAP grid cell. These records were produced using a stochastic daily weather generator (WGEN), which they modified to better utilize temporal statistics created by its accompanying parameterization program (WGENPAR). Parameterization of WGEN was based on daily records from 870 stations. WGEN was run for each grid cell with parameters assigned from the closest station. Climate records created by WGEN have realistic daily variances and temporal auto-correlations and maintain physical relationships between daily precipitation and temperature (Hoogenboom et al., 1995).

To obtain a one-year daily series, they first produced a 20-year weather record using WGEN. From this 20-year record, they derived the VEMAP characteristic year by choosing 12 individual months whose monthly means most closely matched the corresponding long-term historical monthly means. Daily values of the selected months were adjusted so that their sum (for precipitation) or mean (for temperature) exactly matched the historical long-term monthly means (Hoogenboom et al., 1995).

D.1.2. Solar radiation and humidity records

CLIMSIM was used to generate daily records of solar radiation and surface air humidity from daily maximum and minimum temperatures and precipitation. Six solar radiation variables were produced: total incident solar radiation at the surface (sr), sr as a fraction of potential total solar radiation at the top of the atmosphere (fsr) and at the surface (fsr_sfc), potential total solar radiation at the top of the atmosphere (psr) and at the surface (psr_sfc), and mean daily irradiance at the surface (irr). Humidity variables generated were vapor pressure (vp) and mean daylight relative humidity (rh). Because of the biases in the method used in CLIMSIM to generate humidities from daily minimum temperature, daily vapor pressure values were adjusted so that monthly means match the long-term means of Marks (1990). Because solar radiation and humidity data are based on temperatures and precipitation that are constrained to match their long-term means, and because the humidity data are additionally constrained by the Marks (1990) means, monthly means of the solar radiation and humidity daily values are taken to represent the climatological means of these variables (Kittel et al., 1995).

D.1.3. Maximum, minimum and mean temperature

Long-term monthly mean daily maximum and minimum temperatures were interpolated to the VEMAP grid from 4613 station 1961-1980 normal (NCDC 1992, dataset TD-9641). Station values were adiabatically lowered to sea level, interpolated to the 0.5° VEMAP grid, and then readjusted to the new grid elevation. Mean temperatures were computed as a simple average of the gridded maximum and minimum monthly temperatures (Kittel et al., 1995).

D.1.4. Precipitation

Long-term mean monthly precipitation was spatially aggregated from a 10-km gridded U.S. dataset developed using PRISM. PRISM models precipitation distribution by (1) dividing the terrain into topographic facets of similar aspect, (2) developing precipitation-elevation regressions for each facet type for a given region based on station data, and (3) using these regressions to spatially extrapolate station precipitation to 10-km cells that are on similar facets (Kittel et al., 1995).

D.2. Model Selection for 2050 climate: HADCM2

The recent future climate experiments performed at the Hadley Center have used the new Unified Model. These experiments represent a large step forward in the way climate change is modeled by GCMs and raises new possibilities for scenario construction (Mitchell et al., 1995; Johns et al., 1997). This experiment has overcome some of the major difficulties that were associated with the previous generations of equilibrium and transient climate change experiments (Johns et al., 1997).

The Unified Model has been slightly modified to produce a new coupled ocean atmosphere GCM that can be used to perform climate change experiments. This new model has been termed HADCM2 and it has been used to perform a series of transient climate change experiments that have been perturbed using historic greenhouse gas and sulfate aerosol forcing. HADCM2 has a spatial resolution of 2.5 ° x 3.75 ° (latitude by longitude) and the representation produces a grid box resolution of 96 x 73 grid cells. This produces a surface spatial resolution of about 417 x 278 km reducing to 295 x 278 km at 45 ° north and south (Figure 6).

The atmospheric component of HADCM2 has 19 levels and the ocean component 20 (see conceptual diagram of HADCM2 in Figure 7). The equilibrium sensitivity of HADCM2, that is the global-mean temperature response to a doubling of effective CO_2 concentration, is 2.5 °C. This is somewhat lower than most other GCMs (IPCC, 1992).

UKTR and other previous ‘first-generation’ transient climate change experiments simulated the response of the coupled-ocean atmosphere system to a gradual increase in equivalent CO2 concentration. These were, however, ‘cold-start’ experiments that did not take into account the historic forcing of the ocean-atmosphere system. Similarly, the negative radiative forcing effects of sulfate aerosols were not included in the early experiments. In order to undertake a ‘warm-start’ experiment it is necessary to perturb the model with a forcing from an early historical era, when the radiative forcing was relatively small compared to the present. The Hadley center started theoretical experiments with forcing from the middle industrial era, about 1860 (Figure 8).

The greenhouse gas only integration, HADCM2GHG used the combined forcing of all the greenhouse gases as an equivalent CO_2 concentration. HADCM2SUL used the combined equivalent CO_2 concentration plus the negative forcing from sulfate aerosols. HADCM2GHG simulated the change in forcing of the climate system by greenhouse gases since the early industrial period. There is a small amount of forcing (0.4 Wm^{-2}) prior to this simulation period representing the small increase in greenhouse gases from 1765 to 1860. The addition of the negative forcing effects of sulfate aerosols represents the direct radiative forcing due to anthropogenic sulfate aerosols by means of an increase in clear-sky surface albedo proportional to the local sulfate loading (Carnell and Senior, 1998). The indirect effects of aerosols were not simulated (Figure 9).

The modeled control climate (HadCM2CON) shows a negligible long term trend in surface air temperature over the first 400 years. The trend is about +0.04 °C per century, which is comparable to other such experiments. HadCM2CON represents an improvement over UKTR and UKHI. The experiments performed have simulated the observed climate system using estimated forcing perturbations since 1860. Johns et al., (1997) and Mitchell et al., (1995) have established that HadCM2's sensitivity is consistent with the real climate system. The agreement between the observed global-mean temperature record and that produced in these experiments is better for HadCM2SUL than for HadCM2GHG. This implies that HadCM2SUL has captured the observed signal of global-mean temperature changes better than HadCM2GHG for the recent 100-year record.

Figure 10 illustrates the conceptual global-mean temperature time-series for three warm-start transient climate change integration's: GHG (representing HadCM2GHG); SUL (representing HadCM2SUL); and CON (representing (HadCM2CON). The results from GHG and SUL can be fixed directly to calendar years. To construct a scenario that would represent the global-mean temperature change from the start of the HadCM2SUL, t1 (i.e. 1861-90) to present t2 (i.e. 1961-90) then a simple subtraction of t2-t1 is required. Most impacts assessments are based upon the changes from the present (as represented by t2) to a given period in the future (t3), a future climate scenario can, therefore, be constructed by, t3-t2 (2070-2099) – (1961-

1990). In this study we will use the scenario for future climate based on 2050-2059 climate scenarios.

The utilization of these and results from other similar climate change experiments can be used directly for regional scale, climate change scenario construction. Using the results from one single experiment does, however, have limitations as it is not possible to capture the range of uncertainties as described by IPCC. Hence, this study will use two model runs, thought to represent the likely upper and lower boundaries of future (2050's) climate change. Even so the results from HadCM2GHG and HadCM2SUL cannot be treated as a forecast or prediction but as two possible realizations of how the climate system may respond to a given forcing.

The climate data for each location can be evaluated and compared to the different data sources. For the current climate VEMAP data is being used and this can be compared to actual station data (from the station closest to the representative farm), as well as to the two future climate scenario's (Figure 11).

D.3. Climate variability analyses for future climates.

The variability of the climate, under current and future climate scenarios, has been a topic of recent interest for a number of reasons. First, quantification of regional variability under current climatic conditions is necessary before we can really detect climate change. Second, the consequences of changes in variability may be as important as those that arise due to variations in the mean climate state (Carnell and Senior, 1998; Liang et al., 1995; Mearns et al., 1984).

While most climate change agricultural impact studies have analyzed the effects of mean changes of climate variables on crop production, impacts of changes in climate variability have been studied much less (Mearns, 1995). The focus on the effects of mean climate change only provides limited information on how future climates may impact agriculture. Additional information on climate variability is necessary to fully evaluate the possible impacts of climate change on agriculture.

Very few climate change scenarios used for climate change impact analysis have included detailed, explicit changes in variability. In part, this is due to the considerable uncertainty regarding the potential changes in variability associated with changing mean conditions. In addition, there is uncertainty concerning the response of agricultural crops to changes in climate variability, although it is known that such changes could have serious effects (Mearns, 1995). In addition many researchers feel that the changes in variability with climate change are likely to have substantial impact on agriculture (and the rest of the vegetation and society) rivaling the importance of changes in the mean values themselves (Rind, 1991).

D.3.1. Methodology

In order to separate the crop response to mean changes in climate from its response to variability changes, time series of climate variables with changed variability must be constructed or simulated, and the crop model subjected to a range of variability changes. This information can then be used to infer the sensitivity of the cropping system to changes in variability. Similar analysis is then conducted on mean temperatures changes alone and hence, when the analysis is undertaken on future mean and variability changes it is therefore possible to infer what climate changes are causing the cropping system yield changes (Mearns, 1995).

The mean 2050-2059 conditions for each site, individual future years of climate data, and both GCM model runs will be used in this analysis. The variance of the time series will be changed for both temperature (maximum and minimum) and precipitation in a time step of 1 month. This method was chosen as being the simplest possible extension to the way in which mean changes are usually constructed in impact assessments. The variance of each month was altered separately, according to the following algorithm taken from Mearns (1995):

$$X'_t = \mu + \delta^{1/2} (X_t - \mu); \quad [1]$$

and

$$\delta = \sigma'^2 / \sigma^2; \quad [2]$$

where X'_t = new value of climate variable X_t (e.g., monthly mean maximum February temperature for year t); μ = mean of the time series (e.g., the mean of the monthly mean maximum February temperatures for a series of years); δ = ratio of the new to the old variance of the new and old time series; X_t = old value of climate variable (e.g., the original monthly mean February temperature for year t); and σ'^2 = new variance; σ^2 = old variance.

To change the time series so it will have the new variance σ'^2, the variance and mean of the original time series is calculated. Then a new ratio (δ) is chosen (e.g., halving the variance). From the parameters μ, δ, and the original time series, a new time series with variance is calculated according to equation one. This algorithm will be used to change both the maximum and minimum temperatures and the precipitation time series. If any precipitation values become negative they will be removed and a value of zero put in its place.

The variance changes to be used will be to increase the variance by a factor of 2 and reducing it by a factor of 0.5. These changes in variance will then be used with the changes in mean conditions and used to evaluate future changes in cropping systems due to potential climate change. The use of these different climate runs; one from climate time series simulated to reflect only mean climate changes, and one which includes both changes in mean and variability of a simulated climate time series, provides us with a measure of the effect of including variability changes of climate on crop yields (Mearns, 1995).

D.4. Generating daily data

Seven climate scenarios have now been constructed for the crop modeling analysis of potential future climate conditions: (1) VEMAP data for current conditions, (2) HadCM2-GHG, (3) HadCM2-GHG halved variability, (4) HadCM2-GHG doubled variability, (5) HadCM2-SUL, (6) HadCM2-SUL halved variability, and (7) HadCM2-SUL doubled variability data. However, all these data are at a monthly time-step. Climate data for input to the DSSAT suite of crop models are needed at a daily time-step and so the model actually includes a number of weather generators (SIMMETEO and WGEN), which will create daily weather data from monthly variables. The relationships the weather generator uses to create daily data from monthly values are based on current relationships between daily and monthly values, and also on the typical monthly trends. These relationships hold true under current climate conditions but may change under future climate conditions, such as those being modeled here. The use of a number of variability analyses within this study do help negate the problems associated with this assumption as they do produce quite different trends for future data.

SIMMETEO was the weather generator used in this analysis to create the daily weather data. Hence, all seven climate scenario datasets, each for a ten year period (current, or 2050-59) are run through SIMMETEO to create decadal daily datasets of maximum daily temperature, minimum daily temperature, precipitation amount, and solar radiation. This data is now ready to be used with the DSSAT suite of crop models.

D.5. DSSAT

A set of crop models that share a common input-output data format has been developed and embedded in a software package called the Decision Support System for Agrotechnology Transfer (DSSAT). The DSSAT itself is a shell that allows the user to organize and manipulate crops, soils, and weather data and to run crop models in various ways and analyze their outputs (Thornton et. al., 1997).

Crop growth is simulated with a daily time step from sowing to maturity, based on physiological processes that describe the crop's response to soil and aerial environmental conditions. Phasic development is quantified according to the plant's physiological age. In CERES, for example, the crop growth sub-models treat leaf area development, dry matter production, assimilate partitioning, and tiller growth and development. Potential growth is dependent on photosynthetically active radiation and its interception, whereas actual biomass production on any day is constrained by sub-optimal temperatures, soil water deficits, and nitrogen and phosphorus deficiencies. The input data required to run the DSSAT models include daily weather information (maximum and minimum temperatures, rainfall, and solar radiation); soil characterization data (data by soil layer on extractable nitrogen and phosphorous and soil water content); a set of genetic coefficients characterizing the variety being grown; and crop management information, such as emerged plant population, row spacing, and seeding depth, and fertilizer and irrigation schedules (Thornton et al., 1997).

In this study, the SOYGRO, CERES-Maize and CERES-Wheat dynamic growth crop-simulation models are used to determine the effects of future climate change on the yields of soybeans, wheat, and maize in the Midwestern U.S. The choice of these models is based on: (1) their already comprehensive validation across a wide range of different climate and soil conditions, (2) the models simulate crop response to major climate variables, include the effects of soil characteristics on water availability, and are physiologically oriented, and, (3) the models are developed with compatible data structures so that the same soil and climate datasets can be used for all crops which helps in comparison (Adams et al., 1990).

Climate data used for these runs has been implemented into the DSSAT model, and consists of the VEMAP baseline (30 year mean) climate data for each of the 10 study sites (Table 1). This climate data is used to stochastically generate daily weather data in model runs, using variability statistics generated from the original VEMAP dataset. This approach of using monthly data to generate daily data will allow us to play with the results more. This method will be used to generate "expected values" for crop yields under current and future climate scenarios, and under differing climate variability scenarios.

The sensitivity analysis features of DSSAT will be used to determine the effects of differing climatic conditions upon differing combinations of planting and harvest dates. Given the assumptions currently made in DSSAT, it proves to be an effective modeling tool for studying the impact of potential climate change on crop production (Hoogenboom et. al., 1995). Under current climate conditions DSSAT was evaluated by ensuring the crop yield curves were similar to current yields. This was done to provide some form of validation for the DSSAT model at each location. In addition, extensive site specific validation was also undertaken to ensure the model could mirror reality (see Chapter 3). Results from the research of other groups does show that the use of the DSSAT models coupled with a weather generator to simulate daily weather from monthly means values (WGEN or SIMMETEO) does prove to be an efficient method for assessing the impacts of changing climate on agricultural production (Mavromatis and Jones, 1998).

E. LIMITATIONS OF THIS METHODOLOGY

Preparing agriculture for adaptation to climate change requires advance knowledge of how climate will change and when. The direct physical effects on plants and the indirect effects on soils, water etc. must also be understood. Currently, such knowledge is not available for either the direct or indirect potential effects of climate change. However, guidance can be obtained from an improved understanding of current climatic vulnerabilities of agriculture and its resource base. This knowledge can be obtained from the use of a realistic range of climate change scenarios and from the inclusion of the complexity of current agricultural systems and the range of adaptation techniques and policies now available and likely to be available in the future (Rosenburg, 1992).

The results of such research as is discussed here do not predict the future climate, rather this study is simply an evaluation of one possible set of outcomes of our climate system and the possible future changes in agricultural production that would accompany such changes in climate. Such potential changes provide insight into possible larger societal changes needed to control and reduce CO_2 in the atmosphere and also to help decide on appropriate strategies to prepare for change (Adams et al., 1990).

F. FUTURE CLIMATE SCENARIOS AND POTENTIAL RESULTS

The future climate scenarios created for this analysis, using the output from the HadCM2 model and the variability analyses results in significantly changed climate data, when compared to current conditions. The main characteristics of the new climate scenarios are varied but general trends can be distinguished. Table 2 shows the mean monthly change in temperatures and precipitation data for each site, for February and July, from the year 2050 as an example of the changes in these datasets. The data show that under the climate change scenarios there is an appreciable increase in temperatures, specifically in the summer months. July temperatures under the HadCM2-GHG runs range from 5 - 9 °C warmer fro maximum temperatures, and 6 – 9 °C warmer for minimum temperatures. For the HadCM2-SUL runs maximum temperature increases range from 1 - 6 °C warmer, and for minimum temperatures range from 4 – 7 °C warmer. For February temperatures (Table 2) maximum temperatures generally decrease by 1-2 °C or remain the same but minimum temperatures, for both model runs increase by 6 – 9 °C. Thus increases in temperatures are greater for minimum temperatures rather than maximum temperature values, and are greater in the summer months over the winter months.

Precipitation data (Table 2) also have some quite specific patterns with overall trends in monthly precipitation, for both model scenarios, and across the year, showing increasing amounts of precipitation under future climate change. February precipitation amounts increase more under HadCM2-GHG runs, but for both runs average higher than VEMAP data. In July this trend is reversed with the HadCM2-SUL model runs producing increased precipitation compared to the HadCM2-GHG model ruins, although both models are greater than current, VEMAP data. Overall then, future climate data trends across the study area are for increased temperatures, especially for minimum temperature values, and for increased precipitation year-round.

These changes in dominant patterns of temperature and precipitation have important implications for crop growth. Specifically, the effect of will be very important in terms of crop growth modeling. In an analysis on Florida undertaken by Hoogenboom and others (1995), the use of the DSSAT model for climate change analysis did reveal clear temperature signals. The effect of temperature on development in CERES-maize is shown in Figure 12, where the response to growing degree-days is displayed relative to development rate. No development occurs at temperatures below 8 °C; maximum development occurs at 34 °C; and development is reduced at higher temperatures up until 44 °C, above which no development occurs. If this is a maximum temperature sensitivity then maximum temperature reached will become very important in the future climate scenario's, as will the frequency and duration of such occurrences. Similar results are also found for soybeans, using the model SOYGRO. Here the maximum threshold temperature is 45 °C, but development sharply declines above 41 °C (Figure 12). In a study run for a region of central France (Bourges) the researchers, using the HADCM2 model, found that for the decade 2021-2030 the sulphate integration resulted in a decrease of 5.2 % in the mean crop yield. The inclusion of changes in variability (increases) produced crop yield decrease ranging from 6.4-12.3 % (Mavromatis and Jones, 1998).

G. DISCUSSION

Such temperature thresholds will be important to evaluate for the Midwest. Similarly more extreme weather events and increased variability of the weather will also produce some extremely interesting results. From the results of this research an evaluation will also be made as to possible agricultural adaptations to the future climate scenario's that are created. It is hoped that this research will help to highlight areas for future research, in terms of the topics from this study which pertain to potential future problems for this region. Such issues may relate to the implications of both changing mean and variability of the climate, both of which are usually studied separately, not together which is essential for real understanding of future climate impacts. In addition, it is hoped that this research will highlight issues specific to the Midwestern US and hence, enable some early adaptation strategies to be put in place based on this and other similar studies.

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Table 1: The 10 Representative Farms (see Figure 2 for their spatial location)

County names, State	Latitude N	Longitude W
Cass county, Western Illinois	39.996	90.299
Champaign county, Eastern Illinois	40.142	88.22
Columbia county, Eastern Wisconsin	43.45	89.251
Dubois county, Southwest Indiana	38.363	86.89
Grant county, Southwest Wisconsin	42.874	90.724
Randolph county, East-Central Indiana	40.188	84.967
St. Joseph county, South-Central Michigan	41.912	85.505
Tuscola county, Michigan thumb	43.495	83.418
Williamson county, Southern Illinois	37.727	88.928
Wood county, Northwest Ohio	41.325	83.634

Table 2: A comparison of current (VEMAP) and future (HadCM2-GHG and HadCM2-SUL) monthly temperature and precipitation values, for February and July data, for 2050. (Data are created from 'future value – VEMAP value', so a positive value means this variable has increased in the future)

	Feb. Max. Temp. change (°C)	Feb. Min. Temp. change (°C)	July Max. Temp. change (°C)	July Min. Temp. change (°C)	Feb. Precip. change (mm/month)	July Precip. change (mm/month)
W-IL: GHG	0.4	8.68	8.94	8.93	53.78	22.35
W-IL: SUL	-0.24	8.36	5.42	6.40	20.49	35.82
E-IL:GHG	-1.90	8.58	9.34	9.13	52.78	17.35
E-IL:SUL	-2.54	8.26	5.82	6.60	19.49	30.82
E-WI:GHG	-0.05	9.58	7.82	7.79	55.82	10.00
E-WI:SUL	-0.37	9.44	4.17	5.58	34.48	33.27
SW-IN:GHG	-2.06	5.54	4.66	5.84	32.86	15.53
SW-IN:SUL	-3.00	4.95	1.59	3.72	-7.47	37.67
EC-IN:GHG	-0.16	9.54	6.86	7.94	61.01	32.11
EC-IN:SUL	-1.10	8.95	3.79	5.82	25.03	56.67
SC-MI:GHG	0.01	9.15	4.47	5.72	53.76	11.30
SC-MI:SUL	-0.95	8.47	1.39	3.86	24.31	44.95
MI-TH:GHG	-0.19	10.15	4.57	7.02	57.76	27.30
MI-TH:SUL	-1.15	9.47	1.49	5.16	28.31	60.95
S-IL:GHG	-1.10	5.78	8.14	7.83	14.38	18.35
S-IL:SUL	-1.74	5.46	4.62	5.30	-18.91	31.82
NW-OH:GHG	-3.42	9.51	4.28	5.93	60.14	16.53
NW-OH:SUL	-4.74	8.53	1.82	4.21	28.32	60.13
SW-WI:GHG	-0.75	9.28	7.32	6.69	57.82	12.00
SW-WI:SUL	-1.07	9.14	3.67	4.48	36.48	35.27

Where: W-IL is Western Illinois, E-IL is Eastern Illinois, E-WI is Eastern Wisconsin, SW-IN is Southwestern Indiana, EC-IN is East-Central Indiana, SC-MI is South-Central Michigan, MI-TH is the Michigan Thumb, S-IL is Southern Illinois, NW-OH is Northwest Ohio, and SW-WI is Southwest Wisconsin.

Figure 1: Global crop yields and temperature anomalies: 1950-2000

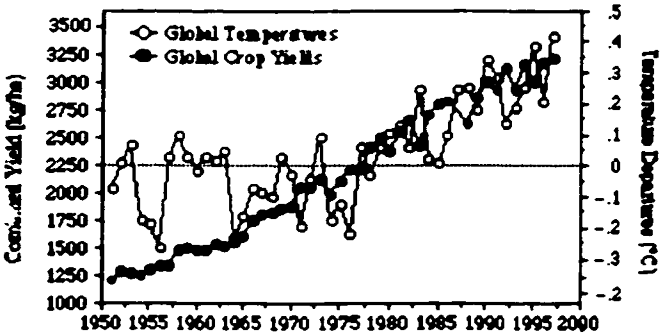


Figure 2: The location of the representative farms across the study region.

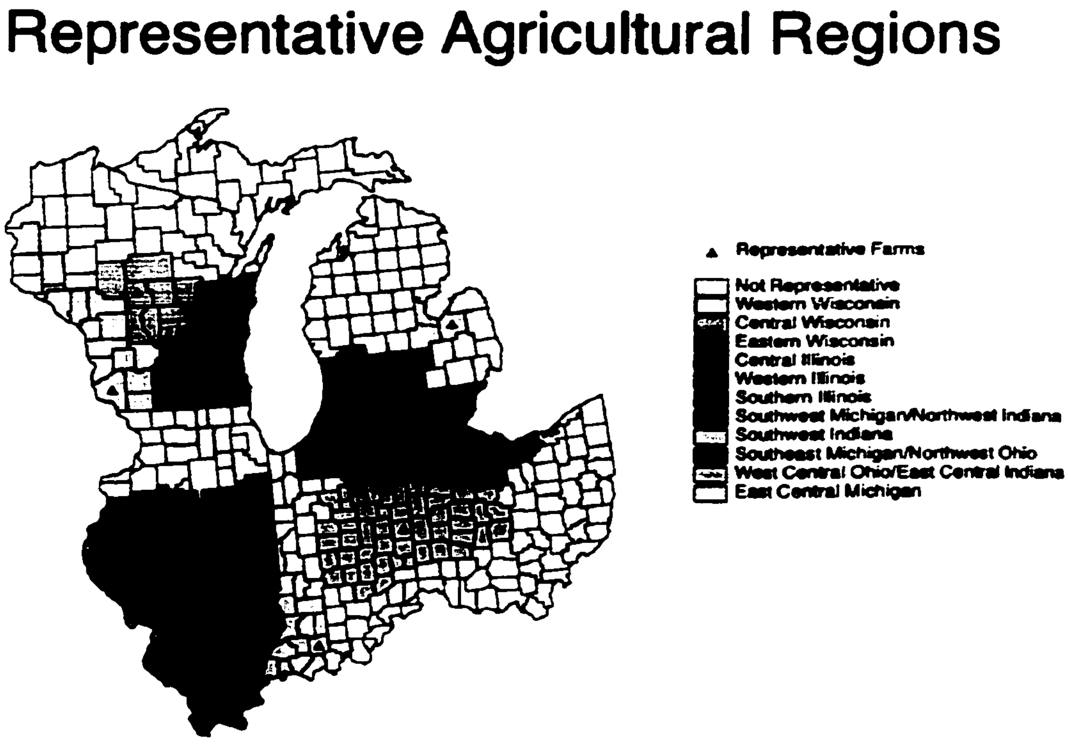


Figure 3: Ecoregions of the Midwestern study area

Developed from "ECOREGIONS OF THE UPPER MIDWEST STATES" by James M. Omernik and Alisa L. Gallant. U.S. Environmental Protection Agency and Northrop Services, Inc. Corvallis, OR. 1988.

Figure 4: The range of predicted changes in global-mean surface temperatures, in °C shown as a band bounded by upper and lower extremes of 7 GCMs, each assuming a 1% increase in CO_2 per year.

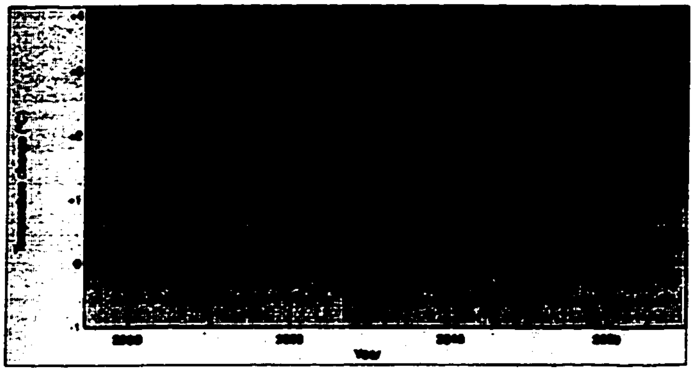


Figure 5: Are we experiencing natural climate variability or global warming?

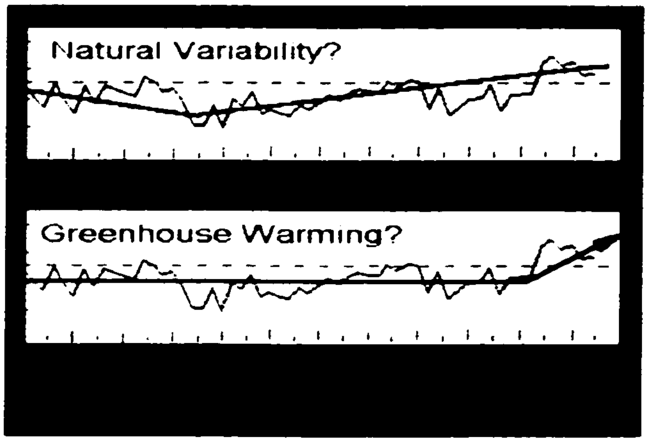


Figure 6: The Land Sea Mask of HADCM2

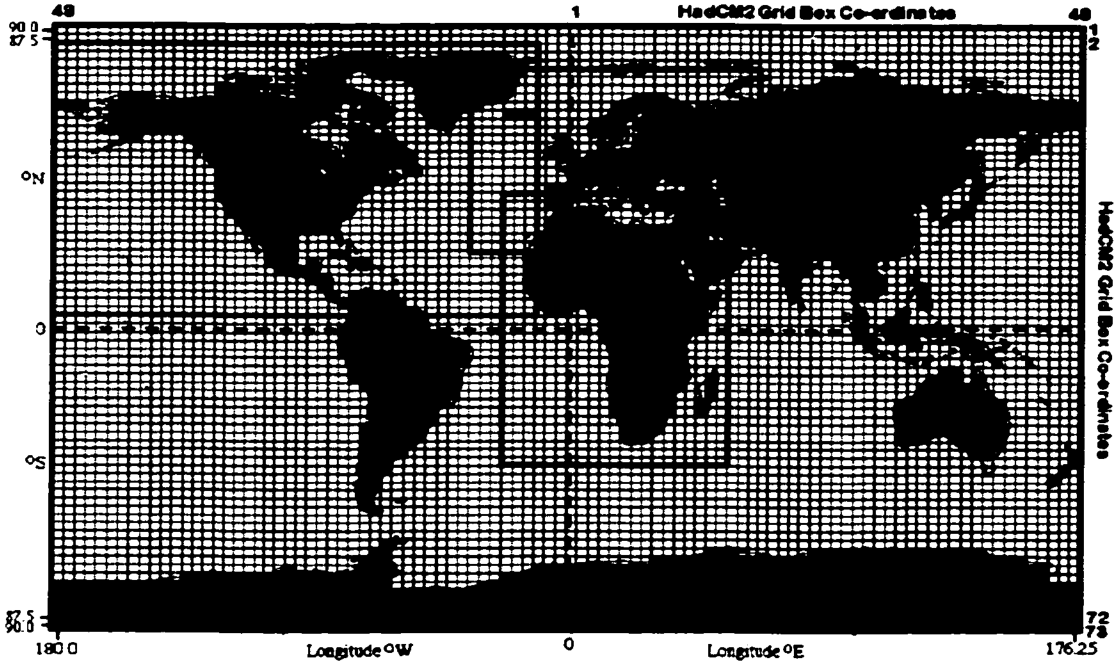


Figure 7: A conceptual diagram of HADCM2

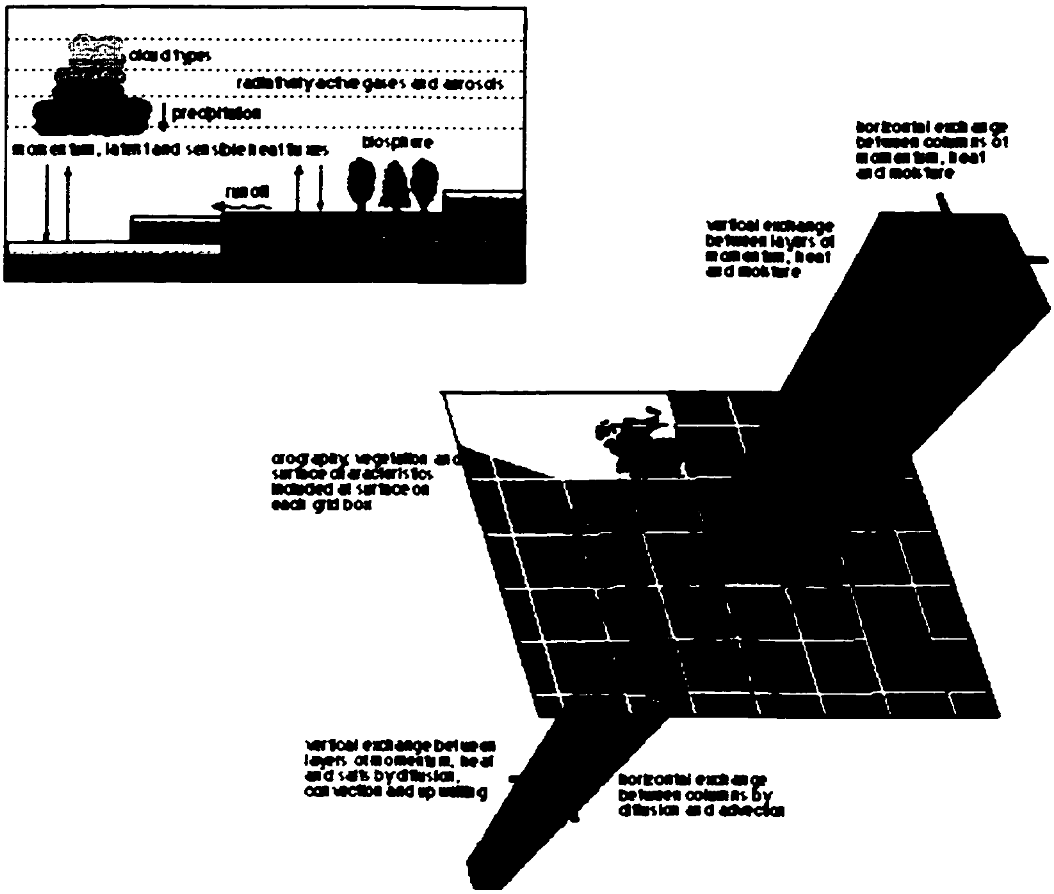


Figure 8: HADCM2 Forcing Scenarios

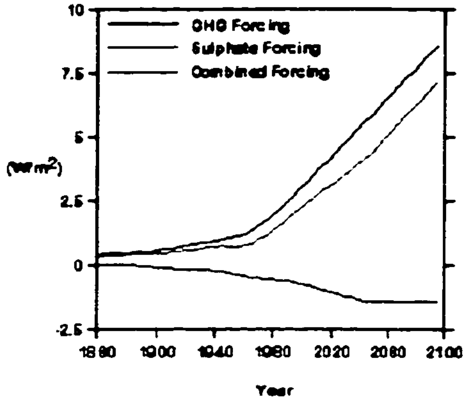


Figure 9: Modeled global mean temperature time series for HADCM2CON, HADCM2GHG, and HADCM2SUL.

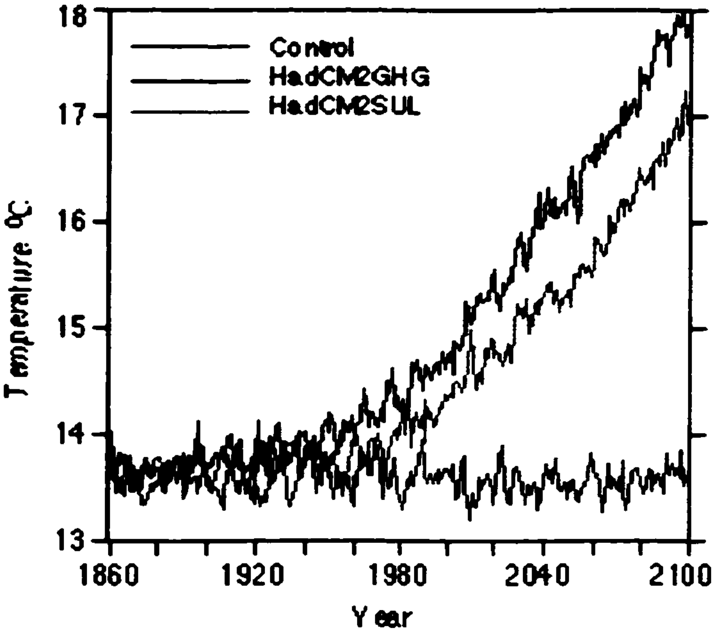


Figure 10: Conceptual global-mean temperature time series for three warm-start transient climate change integration's.

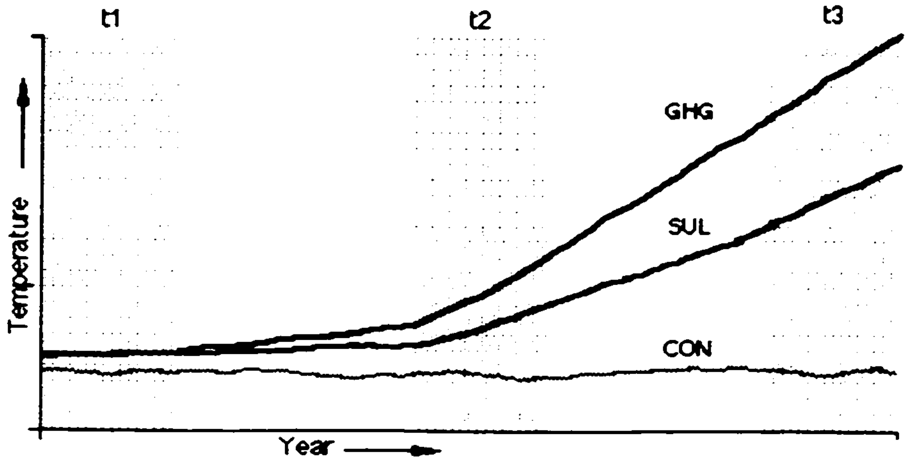


Figure 11: Comparison of climate datasets used in the analysis for Eastern Illinois for (a) Maximum and minimum mean monthly temperatures, and (b) total monthly precipitation

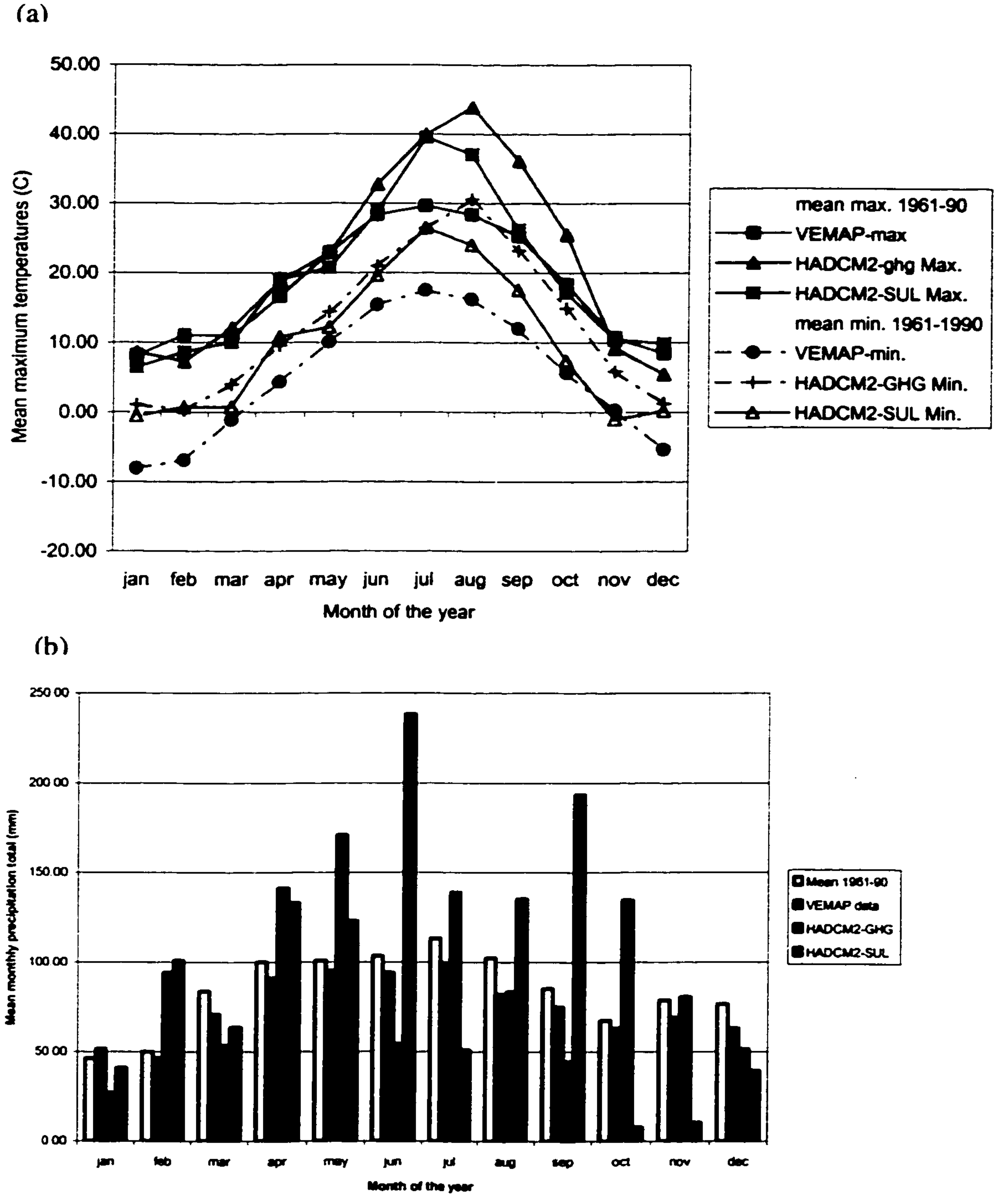
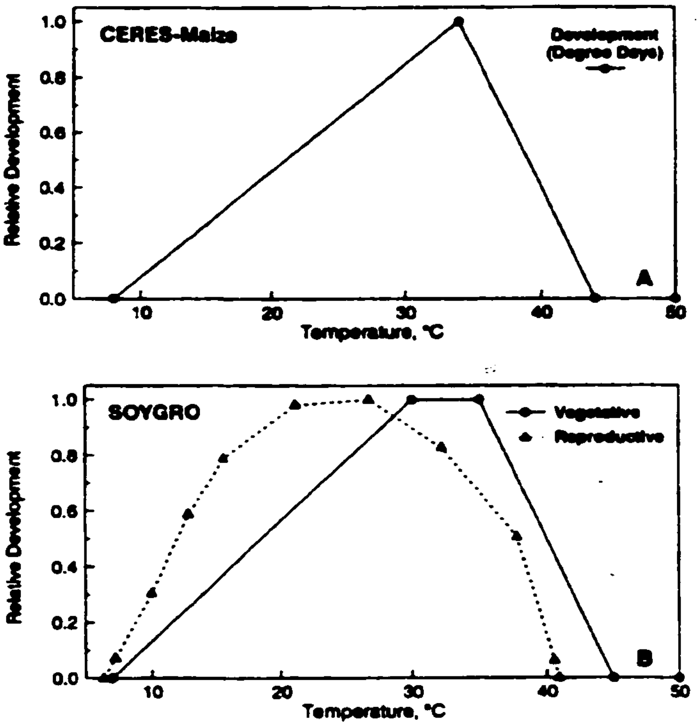


Figure 12: Effect of temperature on (A) corn, and (B) soybean development (Hoogenboom et. al., 1995) for Florida.



Chapter 3:

Consequences of Future Climate Change and Changing Climate Variability on Maize Yields in the Midwestern United States

In Press: *Agriculture, Ecosystems and Environment*

Jane Southworth, J.C. Randolph, M. Habeck, O.C. Doering, R.A. Pfeifer,
D.G. Rao, and J.J. Johnston

Abstract

Any change in climate will have implications for climate-sensitive systems such as agriculture, forestry, and some other natural resources. With respect to agriculture, changes in solar radiation, temperature, and precipitation will produce changes in crop yields, crop mix, cropping systems, scheduling of field operations, grain moisture content at harvest, and hence, on the economics of agriculture including changes in farm profitability. Such issues are addressed for ten representative agricultural areas across the Midwestern Great Lakes region, a five-state area including: Indiana, Illinois, Ohio, Michigan, and Wisconsin. This region is one of the most productive and important agricultural regions in the world, with over 61% of the land use devoted to agriculture.

Individual crop growth processes are affected differently by climate change. A seasonal rise in temperature will increase the developmental rate of the crop, resulting in an earlier harvest. Heat stress may result in negative effects on crop production. Conversely, increased rainfall in drier areas may allow the photosynthetic rate of the crop to increase, resulting in higher yields. Properly validated crop simulation models can be used to combine the environmental effects on crop physiological processes and to evaluate the consequences of such influences. With existing hybrids, an overall pattern of decreasing crop production under scenarios of climate change was found, due primarily to intense heat during the main growth period. However, the results changed with the hybrid of maize (*Zea mays* L.) being grown and the specific location in the study region. In general, crops grown in sites in northern states had increased yields under climate change, with those grown in sites in the southern states of the region having decreased yields under climate change. Yields from long-season maize increased significantly in the northern part of the study region under future climate change. Across the study region, long-season maize performed most successfully under future climate scenarios compared to current yields, followed by medium-season and then short-season varieties. This analysis highlights the spatial variability of crop responses to changed environmental conditions. In addition, scenarios of increased climate variability produced diverse yields on a year-to-year basis and had increased risk of a low yield. Results indicate that potential future adaptations to climate change for maize yields would require either increased tolerance of maximum summer temperatures in existing maize varieties or a change in the maize varieties grown.

Keywords: Climate change; Variability; CERES-maize; Maize yields; Agriculture, Midwestern United States

1. Introduction

Interest in the consequences of increasing atmospheric CO_2 concentration and its role in influencing climate change can be traced as far back as 1827, although more commonly attributed to the work of Arrhenius (1896) and Chamberlain (1897), as cited in

Chiotti and Johnston (1995). A century later, concern over climatic change has reached global dimensions and concerted international efforts have been initiated in recent years to address this problem (Intergovernmental Panel on Climate Change (IPCC), 1995; 1990). Future climate change could have significant impacts on agriculture, especially the combined effects of elevated temperatures, increased probability of droughts, and a reduced crop-water availability (Chiotti and Johnston, 1995).

Based on climate records, average global temperatures at the earth's surface are rising. Since global records began in the mid-19th century, the five warmest years have occurred during the 1990s and ten of the eleven warmest years have occurred since 1980 (Pearce, 1997). Based on a range of several current climate models (IPCC, 1995; 1990), the mean annual global surface temperature is projected to increase by 1° to 3.5° C by the year 2100 and there will be changes in the spatial and temporal patterns of precipitation (IPCC, 1995).

The variability of the climate, under current and future climate scenarios, has been a topic of recent interest for a number of reasons. The consequences of changes in variability may be as important as those that arise due to variations in mean climatic variables (Hulme et al., 1999; Carnell and Senior, 1998; Semenov and Barrow, 1997; Liang et al., 1995; Rind, 1991; Mearns et al., 1984). While most studies of climate change impacts on agriculture have analyzed effects of mean changes of climatic variables on crop production, impacts of changes in climate variability have been much less studied (Mearns et al., 1997; Mearns, 1995).

Within more recent historical records, there have been significant periods of climatic fluctuations such as the dustbowl conditions of the 1930s in the United States, when the dramatic and negative effects of climate variability on agriculture were realized. Katz and Brown (1992) showed that for a given climate variable a change in the variance has a larger effect on agricultural cropping systems than does a change in the mean. The effect of possible changes in climatic variability remains a significant uncertainty that deserves additional attention within integrated climate change assessments (Barrows et al., 1996; Mearns et al., 1996; Semenov et al., 1996). The study of economic effects of climate change on agriculture is particularly important because agriculture is among the more climate sensitive sectors (Kane et al., 1992).

Changes in climate will interact with adaptations to increase agricultural production affecting crop yields and productivity in different ways depending on the hybrids and cropping systems in a region. Important direct effects will be through changes in temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development (Saarikko and Carter, 1996). Also, an increased atmospheric CO_2 concentration could have a beneficial effect on the growth of some species.

Indirect effects will include potentially detrimental changes in diseases, pests, and weeds, the effects of which have not yet been quantified in most studies. Evidence continues to support the findings of the IPCC that "global agricultural production could be maintained relative to baseline production" for a growing population under 2 x CO_2 equilibrium climate conditions (Rosenzweig and Hillel, 1998; Rosenzweig and Hillel, 1993). In middle and high latitudes, climate change will extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvesting, and the possibility of two or more cropping cycles during the same season. Climate change also will modify rainfall, evaporation, runoff, and soil moisture storage. Both changes in total seasonal precipitation or in its pattern of variability are important to agriculture. Moisture stress and/or extreme heat during flowering, pollination, and grain filling is harmful to most crops, such as maize, soybeans, and wheat (Rosenzweig and Hillel, 1993), the most important commodity crops in the Midwestern United States.

In world markets the United States accounts for more than 25 percent of the global trade in wheat, maize, soybeans, and cotton (USDA, 1997; Adams et al., 1999). An important question concerns the ability of North American agriculture to adapt to changing climatic conditions. Warmer climate scenarios (2°-5° C increases in North America) have yielded estimates of negative impacts in eastern, southeastern, and Maize Belt regions and positive effects in northern plains and western regions. More moderate warming produced estimates of predominately positive effects in some warm-season crops (IPCC, 1995).

Agricultural systems are managed and farmers always have a number of possible adaptations or options open to them. These adaptation strategies may potentially lessen future yield losses from climate change or may improve yields in regions where beneficial climate changes occur (Kaiser et al., 1995). Thus, agricultural production responds both to physiological changes in crops due to climate change and also to changes in agricultural management practices, crop prices, costs and availability of inputs, and government policies (Adams et al., 1999).

This research addresses the issues of changing mean climatic conditions and changes in the variability of climate around these means. The occurrence and frequency of extreme events will become increasingly important. This study addresses these issues for ten representative agricultural areas in the Midwestern United States for three hybrids of maize in terms of their current and future yields. Changes in climatic patterns may result in spatial shifts of agricultural practices, thereby impacting current land use patterns. Specifically this research addresses (1) how the mean changes in future climate will affect maize yields across the study region for two future climate scenarios, (2) how the changes in climate variability, in addition to changes in the mean, affect potential future maize yields, (3) the implications of such changes spatially, examining potential future gains and losses, and (4) some possible future adaptation strategies.

2. Methods and materials

2.1. Study region

The Midwestern Great Lakes region (Indiana, Illinois, Ohio, Michigan, and Wisconsin) was divided into ten agricultural areas based on climate, soils, land use, and current agricultural practices. Representative farms were created in each area based upon local characteristics and farm endowments (Figure 1). This region is one of the most productive and important agricultural regions in the world (Smith and Tirpack, 1989).

2.2. Maize crop model

The Decision Support System for Agrotechnology Transfer (DSSAT) software is a set of crop models that share a common input-output data format. The DSSAT itself is a shell that allows the user to organize and manipulate crops, soils, and weather data and to run crop models in various ways and analyze their outputs (Thornton et al., 1997; Hoogenboom et al., 1995). The version of DSSAT used in this analysis was that supplied by ISBNAT, which is DSSAT 3.5.

Crop growth was simulated using the CERES-maize model, with a daily time step from sowing to maturity, based on physiological processes that describe the crop's response to soil and aerial environmental conditions. Phasic development is quantified according to the plant's physiological age. In CERES-maize, sub-models treat leaf area development, dry matter production, assimilate partitioning, and tiller growth and development. Potential growth is dependent on photosynthetically active radiation and its interception, whereas actual biomass production on any day is constrained by sub-optimal temperatures, soil water deficits, and nitrogen and phosphorus deficiencies. The input data required to run the CERES-maize model includes daily weather information (maximum and minimum temperatures, rainfall, and solar radiation); soil characterization data (data by soil layer on extractable nitrogen and phosphorous and soil water content); a set of genetic coefficients characterizing the hybrid being grown (Table 1); and crop management information, such as emerged plant population, row spacing, and seeding depth, and fertilizer and irrigation schedules (Thornton et al., 1997). The soil data were obtained from U.S. Soil Conservation Service (SCS; now known as the Natural Resources Conservation Service) for the ten farm sites. The model apportions the rain received on any day into runoff and infiltration into the soil, using the runoff curve number technique. A runoff curve number was assigned to each soil, based on the soil type, depth and texture as obtained from the STATSGO databases.

Concentrations of nitrogen and phosphorous in the soil were not limiting to crop growth and these modules are turned off within the CERES-maize model runs.

The CERES-maize model includes the capability to simulate the effects of increased atmospheric CO_2 concentrations on photosynthesis and water use by the crop.

Daily potential transpiration calculations are modified by the CO_2 concentrations (Lal et al., 1998; Dhakhwa et al., 1997; Philips et al., 1996). Hence, under current conditions the model can run under the current atmospheric CO_2 concentration, approximately 360 ppmv. However, when evaluating crop growth under changed climate scenarios, which are based on the assumption of global warming due to increased concentration of CO_2 (and other greenhouse gases), the CO_2 concentration was increased accordingly. The atmospheric CO_2 concentration for the future climate scenarios used in this research, based on the years 2050 through 2059, is 555 ppmv.

CERES-maize does not have an algorithm that "kills" maize as a result of spring freezes. Hence, in this analysis whenever a minimum air temperature of –2.0° C or less occurred during the spring (Julian Days 1-180) and after the emergence date, growth was terminated. This value of termination was based on discussion with Dr. Joe Ritchie (pers. comm., 1999) as being a realistic number for freeze loss of maize.

The selection of CERES-maize as the model for this research was based on: (1) the daily time step of the model allows us to address the issue of changes in planting dates, (2) plant growth dependence on both mean daily temperatures and the amplitude of daily temperature values was desired (not just a daily mean temperature growth dependence as for EPIC), (3) the model simulates crop response to major climate variables, including the effects of soil characteristics on water availability, and is physiologically oriented, (4) the model is developed with compatible data structures so that the same soil and climate datasets can be used for all hybrids of crops which helps in comparison (Adams et al., 1990), and (5) comprehensive validation has been done across a wide range of different climate and soil conditions, and for different crop hybrids (Semenov et al., 1996; Wolf et al., 1996; Hoogenboom et al., 1995).

2.3. Crop model validation

CERES-maize has been extensively validated at sites both in the United States and abroad (Dhakhwa et al., 1997; Hoogenboom et al., 1995). Mavromatis and Jones (1998) found that using the CERES-wheat model coupled with a weather generator (WGEN or SIMMETEO) to simulate daily weather from monthly mean values is an efficient method for assessing the impacts of changing climate on agricultural production. Properly validated crop simulation models can be used to determine the influences of changes in environment, such as climate change, on crop growth (Peiris et al., 1996).

Intensive site-specific validation was also undertaken to ensure the model could mirror reality in the representative agricultural areas. Detailed experimental farm level data were used to ensure that yields produced by the model reflected the actual yields in each representative agricultural area. CERES-maize was initially validated using experimental data reported by Nafziger (1994) for maize planted at two locations in Illinois, USA (Figure 2a). Experimental data were available for four planting dates over the period 1987-90, and measured yields were compared against yields simulated using CERES-maize. Simulated yields corresponded to within +/- 10% of the observed maize yields.

In addition, each representative farm was validated using historical yield data and past daily climate information. This validation was used to ensure the model could replicate past yields, at each location being modeled, for longer-season (currently grown) maize varieties and that the medium and short-season maize varieties showed the correct trends based on expert opinions of agronomists (Figure 2b).

In addition, CERES-maize was used to simulate the relationships between planting date and yield (expressed as a percentage of the highest yield observed for any combination of hybrid and planting date) for long, medium, and short-season maize varieties for twenty different planting dates. The relationship between planting date and yield suggest that long-season maize has higher yields than medium and short-season maize for earlier planting dates, medium-season maize has the highest yields for the middle planting dates, and short-season maize has the highest yields for late planting dates. These results are consistent with expectations about hybrid performance in this region. Further, the close match between the long-season hybrid performance and agronomist expectations gives us confidence that the model is able to describe the relationship between planting date and maize yield for these locations (Figure 2b). Similar results have been obtained for all ten representative agricultural areas in the study region.

2.4. Current climate analysis: VEMAP

The VEMAP dataset includes daily, monthly, and annual climate data for the conterminous United States including maximum, minimum, and mean temperature, precipitation, solar radiation, and humidity (Kittel et al., 1996). The VEMAP baseline (30-year historical mean) climate data was used for each of the ten representative agricultural areas in the study region. The weather generator SIMMETEO (as used in DSSAT version 3.5) used these climate data to stochastically generate daily weather data in model runs. This approach of using monthly data to generate daily data allowed us to generate variability scenarios. The climate variables distribution patterns mimic the current climate variables distributions. As there is no way to know future distributions, they are based on current patterns. Sensitivity analysis determined the effects of differing climatic conditions upon differing combinations of planting and harvest dates.

2.5. Future climate scenarios

This research used the Hadley Center model 'HadCM2' from England for future climate scenario data. This model was created from the Unified Model, which was modified slightly to produce a new, coupled ocean-atmosphere GCM, referred to as HadCM2. This has been used in a series of transient climate change experiments using historic and future greenhouse gas and sulfate aerosol forcing. These models simulate time-dependent climate change (Barrow et al., 1996). Transient model experiments are considered more physically realistic and complex, and allow atmospheric concentrations of CO_2 to rise gradually over time (Harrison and Butterfield, 1996). The results from this model have been validated at a number of locations. HadCM2 is also one of the models used in the U.S. National Assessment project.

HadCM2 has a spatial resolution of 2.5° x 3.75° (latitude by longitude) and the representation produces a grid box resolution of 96 x 73 grid cells, which produces a surface spatial resolution of about 417 x 278 km reducing to 295 x 278 km at 45° north and south. The atmospheric component of HadCM2 has 19 levels and the ocean component 20 levels. The equilibrium sensitivity of HadCM2, that is the global-mean temperature response to a doubling of effective CO_2 concentration, is 2.5° C, somewhat lower than most other GCMs (IPCC, 1990).

The greenhouse-gas-only version, HadCM2-GHG, used the combined forcing of all the greenhouse gases as an equivalent CO_2 concentration. HadCM2-SUL used the combined equivalent CO_2 concentration plus a negative forcing from sulfate aerosols. HadCM2-GHG simulated the change in forcing of the climate system by greenhouse gases since the early industrial period. There is a small amount of forcing (0.4 $W\ m^{-2}$) prior to this simulation period representing the small increase in greenhouse gases from 1765 to 1860. The addition of the negative forcing effects of sulfate aerosols represents the direct radiative forcing due to anthropogenic sulfate aerosols by means of an increase in clear-sky surface albedo proportional to the local sulfate loading (Carnell and Senior, 1998). The indirect effects of aerosols were not simulated.

Our research used the period of 2050 to 2059 for climate scenarios. However, using a single scenario has limitations, as it is not possible to capture the range of uncertainties as described by the IPCC. This study used two model scenarios to represent the likely upper and lower boundaries of future (2050's) climate change. The results from HadCM2-GHG and HadCM2-SUL cannot be viewed as a forecast or prediction, but rather as two possible realizations of how the climate system may respond to a given forcing. A comparison of the main three climate datasets (Table 2) highlights the differences in projected mean climate data for the study region. Also, a climate variability analysis was conducted on these two scenarios, thus increasing the number of future climate scenarios to six. Hence, a range of probable climate change scenarios were examined to determine their impacts on maize growth.

2.6. Climate variability analysis

In order to separate crop response to changes in climatic means from its response to changes in climate variability it is necessary first to model the impacts of mean temperature changes on crop growth. Then a time series of climate variables with changed variability can be constructed and added to the mean change scenarios. Hence, when the analysis is undertaken on future mean and variability changes it is therefore possible to infer what type of climate change caused changes in yield (Mearns, 1995).

The mean conditions for the period 2050-2059 for each location, individual future years of climate data, and both GCM model runs were used in this analysis. The variance of the time series was changed for both temperature (maximum and minimum) and precipitation in time steps of one month. The variance of each month was altered separately, according to the following algorithm from Mearns (1995):

$$X'_t = \mu + \delta^{1/2} (X_t - \mu); \quad \text{[Equation 1]}$$

and

$$\delta = \sigma'^2 / \sigma^2; \quad \text{[Equation 2]}$$

where X'_t = new value of climate variable X_t (e.g., monthly mean maximum February temperature for year t); μ = mean of the time series (e.g., the mean of the monthly mean maximum February temperatures for a series of years); δ = ratio of the new to the old variance of the new and old time series; X_t = old value of climate variable (e.g., the original monthly mean February temperature for year t); σ'^2 = new variance; and σ^2 = old variance.

To change the time series to have a new variance σ'^2, the variance and mean of the original time series was calculated and then a new ratio (δ) was chosen (e.g., halving the variance). From the parameters μ, δ, and the original time series, a new time series with variance was calculated using equation one. This algorithm was used to change both maximum and minimum temperatures and the precipitation time series. This simple method, as developed by Mearns (1995) was used despite more complex methodologies being developed, due to the comparisons of variability techniques. Mearns et al., (1996; 1997) illustrated the results obtained from the more computationally advanced, upper-level statistical techniques were surprisingly similar to prior results from the more statistically simple methodologies. If anything, these researchers noted a likelihood of underestimating the negative impacts of climate variability on crop yields using the simpler techniques, but in these analyses the differences were quite minor. The approach used here permits the incorporation of changes in both the mean and the variability of future climate in a computationally inexpensive, highly consistent, and reproducible manner.

2.7. Model and data limitations

This study does not attempt to predict future climate, but rather, is an evaluation of possible future changes in agricultural production in the Midwestern United States that might result from future changes in climate. Such potential changes provide insight into possible larger societal changes needed to control and reduce CO_2 in the atmosphere and to help select appropriate strategies to prepare for change (Adams et al., 1990).

The CERES-maize model, which is a deterministic model in that using identical input files will produce the same output, as with all models, contains several assumptions. Weeds, insects and crop diseases have no detrimental effect on yield. Also, extreme climate-related events such as droughts or floods are not taken into account by the model in terms of extreme crop losses resulting from such events.

Other limitations relate to the simplified reality represented by the representative farms, the use of a single soil type at each location, and hence, the loss of the spatial variability of soils, although the selected soil type was that predominant at each location. However, the extensive validation and analysis at the farm level is in itself a more detailed analysis than previously undertaken.

Preparing agriculture for adaptation to climate change requires advance knowledge of how climate will change and when. The direct physical effects on plants and the indirect effects on soils, water, and other biophysical factors also must be understood. Currently, such knowledge is not available for either the direct or indirect effects of climate change. However, guidance can be obtained from an improved understanding of current climatic vulnerabilities of agriculture and its resource base. This knowledge can be obtained from the use of a realistic range of climate change scenarios and from the inclusion of the complexity of current agricultural systems and the range of adaptation techniques and policies now available and likely to be available in the future (Rosenburg, 1992).

3. Results

3.1. Consequences of changing mean climate and climate variability on maize yields

Changes in yield were evaluated by comparing the future maize yields to the current VEMAP yields, on the same hybrids, and then stating the change as percentage difference. Decreases in yield were greatest in doubled variability scenarios. Decreases in yield were greater for HadCM2-GHG scenarios than for HadCM2-SUL scenarios. Increasing the variability of the future climate scenarios increased the variability of the year-to-year crop yields obtained from the DSSAT model. The greater variance associated with the HadCM2-GHG climate scenario is due to the more extreme increases in mean temperatures associated with this climate scenario, compared to the lesser increases for the HadCM2-SUL climate scenario.

Long-season maize in all future climate scenarios (Figure 3) clearly showed decreases in yields in the southern and central locations. The decreases range from 0 to -45 % as compared to yields estimated using VEMAP data. The largest decreases in yield occurred in western Illinois for all future climate scenarios. In contrast, the northern locations showed increases in yields under these same future climate scenarios. In the four northernmost agricultural areas (east central Michigan, southwest Michigan, eastern Wisconsin, and western Wisconsin) increases in maize yield ranged from 0.1 to 45% as compared to yields using VEMAP data. An exception to this pattern was for the HadCM2-GHG scenario with doubled variance, where southwestern Michigan and western Wisconsin had –0.1 to –10 % decreases in yield. The doubled variability runs of both scenarios resulted in extreme decreases in yield in the southern locations, and less significant increases in yield in the northern locations as compared to unchanged or halved variability runs. The greatest gains in yield occurred in the halved variability scenarios because the occurrence of very low or zero yields decreased substantially in the halved variability scenarios.

Medium-season maize yields (Figure 4) showed dramatic decreases in yields as compared to VEMAP, even in the northern agricultural areas of the study region. Under the HadCM2-GHG and HadCM2-SUL scenarios all regions experienced decreases in yields of maize, ranging from –15.1 to –40 %. In these scenarios no locations experienced increases in yield. Under the doubled and halved variability scenarios, however, the northern most locations showed lesser decreases in yield and even some increases. Values ranged from –30 to 20 % for the halved variability scenarios, and from –40 to 15 % for the doubled variability scenarios. It must be noted that the actual (simulated) yields obtained for medium-season maize are usually higher than those obtained for longer-season maize for all climate scenarios (Table 3).

Short-season maize showed a different pattern with all yields decreasing, as compared to yields using VEMAP data, except in western Illinois (Figure 5). In this agricultural area, yields increased under all HadCM2-SUL scenarios and the halved variability HadCM2-GHG scenario, with increases ranging from 5.1 to 35 %. This difference in pattern relates to the timing of the maize growth stages, within a shorter period of time (compared to medium and longer season varieties) and the coinciding of this timing with the extreme summer temperatures that acts to limit growth. Precipitation is not a limiting factor as yields perform just as poorly when full irrigation is allowed.

3.2. Mean maximum decadal yield versus planting dates

The impact of changing climate on planting dates in terms of the mean maximum decadal yields (Figures 3-5) indicates that under future climate change scenarios later planting dates produced higher yields. In almost all cases (Table 3) the highest mean maximum decadal yield occurs at a later planting date under future climate change, which explains why medium-season maize varieties frequently have higher total yields than the longer season maize. The later planting dates for all maize varieties have the most beneficial impact on medium-season maize. The productivity induced shift to later planting dates is past the current optimal planting dates for longer season varieties and into the medium-season maize optimal planting dates. Such delays in planting dates also have been found by other researchers under future climate change scenarios (Jones et al., 1999).

3.3. *Spring freezes*

In future climate scenarios the frequency of maize-killing freeze events will decrease although under doubled variance scenarios the intensity of the freeze event will increase (Figure 6). This implies that increased frost tolerance is not an important issue for future climate change and maize growth as initially expected.

4. Discussion

4.1. Crop yield changes by region

The future climate scenarios, with increased temperatures and precipitation, resulted in significantly altered maize yields, at each of the ten agricultural areas in the study region.

Across the southern areas yields generally decreased due to the daily maximum temperatures becoming too high and hence, resulting in yield decline. Western Illinois had yield decreases of -10 to -50 % for long-season maize, -10 to -40 % for medium-season maize, and -10 to +40 % for short-season maize. For short-season maize western Illinois was the only location with yield increases, although these increases only occurred under the HadCM2-SUL scenarios and the halved variability HadCM2-GHG scenario, i.e., the less extreme climates. Eastern Illinois had yield decreases of -10 to -40 % for long and medium-season maize, and -30 to -50 % decreases for short-season maize. Southern Illinois yield decreases ranged from 0 to -40 % for long-season maize, -10 to -40 % for medium-season maize, and -30 to -40 % for short-season maize. Results were very consistent across climate scenarios. Southwest Indiana yields decreased between 0 and –20 % for long-season maize, 0 and –30 % for medium-season and short-season maize. East-central Indiana had yield decreases of –10 to –30 % for long-season maize, 0 to –30 % for medium-season maize, and –20 to –50 % for short-season maize.

Agricultural areas in the northern states of the study region typically experienced more increased yields under the six future climate scenarios, especially for long-season maize. Northwest Ohio had yield changes of +10 to –20 % for long-season maize, +20 to –30 % for medium-season maize, and 0 to –30 % for short-season maize. South-central Michigan yield changes ranged from +20 to –10 % for long-season maize, +20 to –20 % for medium-season maize, and –10 to –30 % for short-season maize. The Michigan thumb area experienced the greatest yield increases for long-season maize, with +20 to +50 % increases above current yields, for medium-season maize +20 to –30 % changes in yield, and 0 to – 30 % decreases for short-season maize. Southwest Wisconsin had + 20 to –10 % changes in yield for long-season maize, +10 to –30 % for medium-season maize, and –20 to –50 % changes for short-season maize. Finally, eastern Wisconsin, had yield changes of 0 to +40 % for long-season maize, +20 to –30 % for medium-season maize, and –10 to –40 % for short-season maize.

The results across all ten agricultural areas have some significant and consistent patterns. The two main patterns are: (1) short-season maize has low yields compared to current yields under changed climate scenarios except in western Illinois, and (2) the halved variability climate scenarios produced both the highest maize yield increases and some of the lowest decreases in agricultural areas in the southern states, indicating that changes in future climate variability, producing more extreme climatic events, will be detrimental to future agricultural production. Hence, as this research illustrates, it is extremely important to model both changes in mean and variability of future climate.

Our results indicate that the currently grown (predominant) maize hybrid (long-season maize) will have increased or better yields under future climate conditions, compared to current yields, than will the medium and short-season maize hybrids. However, in terms of actual yield, medium-season maize yields are frequently similar to those obtained from longer-season maize for the same climate scenario. This relates to the timing of the different growth cycles within the summer months, and the negative impacts of extreme temperatures (> 35 °C). Short-season maize does not appear to be as viable under changed climate conditions across the study region, as much of its growth period coincides with the most extreme temperatures.

Spatially, results show that the agricultural areas in the northern states (southwest Wisconsin, eastern Wisconsin, south-central Michigan, northwest Ohio, and the Michigan thumb) will experience increases in maize yields as a result of climate change, while those in the southern and central regions (western Illinois, eastern Illinois, southern Illinois, southwest Indiana, and east-central Indiana) will show a clearly decreasing trend. The more extreme climate scenario, as represented by HadCM2-GHG, results in greater reduction of maize yields than HadCM2-SUL. The HadCM2-GHG scenario produces mean monthly summer temperatures that are 1-4 °C warmer than the HadCM2-SUL scenarios. Increased surface air temperatures result in a reduction in agricultural productivity in many crops due to earlier flowering and a shortening of the grain-fill period. The shorter the crop duration, the lower yield per unit area (Lal et al., 1998), as is seen in results in central and southern locations in the study region. However, in northern locations of the study area, where low temperatures currently limit the grain fill period, increases in temperatures due to climate change will result in the grain filling period lengthening and increased yields.

4.2. Daily maximum temperatures

High temperatures affect agricultural production directly through the effects of heat stress at critical phenological stages in the crop's growth. In maize, high temperatures at the stages of silking or tasseling result in significant decreases in yield. Both the CERES-maize and another crop model, EPIC, use the temperature-sum approach to calculate developmental time, where: Growing Degree Days (GDD) = [(Tmax - Tmin) / 2] – Tbase. In the case of the EPIC model, the only condition is that GDD cannot be less than zero. This has an important implication for climate change studies, because increasing the daily mean temperature in the EPIC model will never directly slow the developmental rate. In the case of CERES-maize, if the maximum daily temperature (Tmax) is above 44° C or the minimum daily temperature (Tmin) is less than the base temperature, then the average 3-hour temperature is calculated for 8 periods of the day using an interpolation scheme. If this 3-hour temperature is greater than the base temperature or less than 44° C, then the 3-hour temperature contributes to the daily temperature to be summed. In addition, if the 3-hour temperature is greater than 34° C, then the developmental rate is assumed to decrease. Using the CERES-maize model, when the maximum daily temperature exceeds 44° C, then the developmental rate will be slowed due to high temperatures. In addition, if the amplitude of daily temperature fluctuations increases to the extent that the maximum daily temperature is exceeding

44 °C or the minimum daily temperature is less than the base temperature, the developmental rate will decrease, even if the mean daily temperature stays the same. In contrast, with the standard GDD approach, such as that used in the EPIC model, only the mean daily temperature effects developmental time, not the amplitude of daily temperature. Again, this has implications for climate change studies, where daily temperature amplitude may change as the climate changes (Riha, 1999; pers. comm.). This inclusion of both the amplitude and the mean temperature is an important reason for the selection of the CERES-maize model.

Using regression analyses, Rosenzweig (1993) found that daily maximum temperatures greater than 33.3° C in July and August were negatively correlated with maize yield in the U.S. Maize Belt and that daily maximum temperatures > 37.7° C caused severe damage to maize. The future climate scenarios used had maximum daily temperatures > 35° C on several days during July and August (Table 4). Results in this table match closely with yield changes with an increased number of days with temperatures greater than 35° C within a given climate scenario, resulting in decreased yields.

Hoogenboom et al., (1995), using the CERES-maize model, found that no maize growth occurred at air temperatures below 8° C; maximum crop growth and grain fill occurred at daily temperatures of 34° C; and growth was reduced at higher temperatures up until 44° C, above which no growth occurred. Due to this temperature sensitivity maximum daily temperature will become important in the future climate scenarios, as will the frequency and duration of such occurrences.

The U.S. Environmental Protection Agency (EPA) found a decrease in maize yields under conditions of future climate change of 4-42 % due to temperatures rising above the range of tolerance for the maize crops (EPA, 1998). Saarikko and Carter, (1996) found that the thermal suitability for spring wheat in Finland could shift northwards by 160-180 km per 1° C increase in mean annual temperature. In these areas of current growth of spring wheat in Finland the timing of crop development under a warmer climate shifts to earlier in the year, thus shortening the development phase, resulting in decreased yields. In northwest India, Lal et al., (1998) found a reduction of 54% in wheat yields with a 4° C rise in mean daily temperatures, when using the CERES-wheat model from DSSAT. Using a doubled atmospheric CO_2 concentration (720 ppmv) from present day and a 5 °C rise in mean daily temperatures, the decrease in yield was only 32 % from current conditions. These results are similar in terms of pattern and trend to those of this research, with increasing summer maximum temperatures resulting in decreased yields.

4.3. Impacts of CO_2 fertilization

This approach, using the CERES-maize model, enables us to model the predicted future climate, and CO_2 levels based on this future climate, and to evaluate the crop response. This research used a future atmospheric CO_2 concentration of 555 ppmv, compared to 360 ppmv for current conditions. For maize, a C4 crop, this response is not as important as for C3 crops such as soybeans. C4 crops are more efficient photosynthetically than C3 plants and show less response to increasing atmospheric CO_2 concentration, which provides a future potential agricultural adaptation of C3 crops over C4 crops due to their enhanced growth functions with higher concentrations of CO_2

(Rosenzweig and Hillel, 1998; Rosenzweig, 1993). Assessment of both the effects increased atmospheric CO_2 concentrations and climatic change impacts on agricultural production is a crucial area of research because the two factors occur together.

4.4. Climate variability impacts on maize yields

The halved variability climate scenarios produced maize yields with the greatest increases in yield for long-season maize. In addition, decreases in yield for the agricultural areas in the southern states, and for the medium-season and short-season maize varieties were much less extreme. These results were expected for the halved variability scenarios which resulted in fewer extreme events (Figure 6, Table 4).

The doubled climate variability scenarios represent the most extreme climate scenarios modeled. In addition, a doubling of current variability conditions is probably at the maximum limit of likely future changes in climate variability. As such, these doubled variability scenarios probably represent the most extreme variability changes that might occur by 2050. Under the doubled variability scenarios, particularly the doubled variability HadCM2-GHG scenario, the greatest decreases in maize yields for long-season maize are found. Medium-season and short-season maize also experience large decreases in yield under these scenarios. The doubled variability scenario also results in highly variable year-to-year variability in maize yields across the ten years modeled and studied. These results are in accordance with those found by other research groups, and are not surprising given the high incidence of days with extreme temperatures, compared to the halved variability scenarios (Table 4). When evaluating all six future climate scenarios in terms of their impacts on Midwestern maize yields it is quite evident that the most detrimental agricultural impacts would arise from a future climate similar to the HadCM2-GHG doubled variability scenario.

More extreme weather events and increased variability of the weather will result in lower maize yields. Philips et al., (1996) studied climate impacts on crop yields in the United States and found that changes in variability affected mean yields less than changes in mean climate, but did affect changes in inter-annual yield variability. Mearns et al., (1996; 1997) found that increases in climate variability, on a scale of doubling current variability, resulted in substantially decreased crop yields for wheat. In addition, they found decreased variability to have little effect on mean yield. Wolf et al., (1996) and Semenov et al., (1996) found that higher temperatures in Rothamsted, U.K. and in Seville, Spain, resulted in lower grain yields for spring wheat. In addition, a doubling of temperature variability resulted in an additional decrease in yield (using the models CERES, AFRCWHEAT and NWHEAT, but not for SIRIUS which had no change) across all sites, which was related to an increased number of days at sub-optimal temperatures. For the same locations Semenov and Barrow, (1997) found that when changes in climate variability were included in the climate change analysis the results were quite different. For wheat yields, a decrease in yield of 20 % was observed when variability was doubled. Again, these results are similar to those reported in this research.

4.5. Potential Adaptations to Climatic Change

Another important area of research concerns possible adaptation strategies to climate change and the effects of those strategies. The most obvious adaptations identified in this research are: (1) the development of a more heat tolerant hybrid of long-season maize and (2) switching from maize (a C4 crop) to soybeans (a C3 crop) to take advantage of increased atmospheric CO_2 concentrations promoting increased growth and greater tolerances for hot temperatures (although how realistic this may be will be dependent on market factors). In fact, increased heat tolerance in short and medium-season maize varieties may provide the opportunity to manipulate planting dates of these hybrids and provide adaptation equal or superior to adaptation of long term varieties under some conditions, which is illustrated by the use of shorter season maize varieties rather than sorghum in recent years in the southwestern United States. Under increased climate variability and increased extreme events, soil moisture management will become more critical and will require improved soil infiltration and water holding capacity. Tillage and cropping systems that yield these benefits will increase in economic value to farmers. Also there will be increased concern about soil erosion with more extreme rain events, especially if agricultural program standards for conservation compliance that limits erosion are tightened.

5. Conclusions

Our primary conclusions are:

- A lengthened growing season, dominated by a central period of high maximum daily temperatures, is a critical inhibitor to maize yields. Late spring and early fall frosts do not affect maize yields.
- The north-south temperature gradient in the Midwestern Great Lakes states is extremely important in influencing patterns of maize yield under future climate conditions.
- Climate variability is a significant factor influencing maize yields because increased climate variability results in the largest decreases in future maize yields.

Understanding responses of individual farms to changes in mean climate and changes in climate variability is essential to understanding the impacts of climate change on agriculture at a regional scale (Wassenaar et al., 1999). The research discussed here is part of a larger project examining possible farm-level adaptations to the potential changes predicted from the crop modeling. Continuing research will incorporate crop modeling of soybeans (DSSAT SOYGRO) and wheat (DSSAT CERES-wheat), both in terms of the potential mean changes in future climate and the potential changes in climate variability. These results will be used as inputs into the Purdue Crop Livestock Program (PC/LP) model for farm level decision analysis. The results from the DSSAT models (CERES-maize, CERES-wheat, and SOYGRO) flow into PC/LP, then as management/economic decisions change the type of production, results are fed back into the crop model for further adjustment to crop production modeling. This will allow the development of farm level strategies to be created and then tested by running back through the model scenarios with the adaptations incorporated.

The approach taken in this research examines adaptation at the farm level. Other research has examined agricultural response to climate change primarily on a regional or national basis. Both are important. However, at the local level, climate change research must include the full spectrum of climate, soils, biology, management, and economics if there is to be any link between analysis and reality. This research provides the scientific basis for strategic planning and risk management by farmers and the agricultural infrastructure to better adapt to changing conditions.

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Table 1: Genetic coefficients for CERES-maize for (a) east-central Indiana, south-central Michigan, eastern Wisconsin, south-west Wisconsin, and the Michigan thumb, and for (b) eastern Illinois, southern Illinois, south-west Indiana, and western Illinois

(a)

Designation	P1[a]	P2[b]	P5[c]	G2[d]	G3[e]	PHINT[f]
Long	320	0.52	940	620	6.0	38.9
Medium	200	0.30	800	700	6.3	38.9
Short	110	0.30	680	820	6.6	38.9

(b)

Designation	P1[a]	P2[b]	P5[c]	G2[d]	G3[e]	PHINT[f]
Long	320	0.52	990	620	6.0	38.9
Medium	200	0.30	843	700	6.3	38.9
Short	110	0.30	716	820	6.6	38.9

[a] Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8° C) during which the plant is not responsive to changes in photoperiod.

[b] Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours).

[c] Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8° C).

[d] Maximum possible number of kernels per plant.

[e] Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).

[f] Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

Table 2: Comparison of HadCM2GHG and HadCM2SUL climate scenario mean monthly maximum and minimum temperature and precipitation values, compared to VEMAP current mean monthly climatic conditions for July

	VEMAP[a]			HadCM2GHG[b]			HadCM2SUL[c]		
Site[d]	Max. Temp (°C)	Min. Temp (°C)	Total monthly Precip. (mm)	Δ in Max. Temp (°C)	Δ in Min. Temp (°C)	Δ in Total monthly Precip. (mm)	Δ in Max. Temp (°C)	Δ in Min. Temp (°C)	Δ in Total monthly Precip. (mm)
E-IL	29.6	17.4	99.0	+9.3	+9.1	+17.4	+5.8	+6.6	+30.8
EC-IN	28.5	16.0	95.0	+6.9	+7.9	+32.1	+3.8	+5.8	+56.7
NW-OH	28.2	15.7	88.0	+4.3	+5.9	+16.5	+1.8	+4.2	+60.1
SC-MI	28.1	15.5	87.0	+4.5	+5.7	+11.3	+1.4	+3.9	+45.0
S-IL	30.8	18.7	98.0	+8.1	+7.8	+18.4	+4.6	+5.3	+31.8
SW-IN	30.7	18.1	114.0	+4.7	+5.8	+15.5	+1.6	+3.7	+37.7
E-WI	27.8	15.1	96.0	+7.8	+7.8	+10.0	+4.2	+5.6	+33.3
SW-WI	28.3	16.2	94.0	+7.3	+6.7	+12.0	+3.7	+4.5	+35.3
W-IL	30.0	17.6	94.0	+8.9	+8.9	+22.4	+5.4	+6.4	+35.8
MI-Th	28.0	14.2	71.0	+4.6	+7.0	+27.3	+1.5	+5.2	+61.0

[a] VEMAP dataset for current climate data.

[b] HadCM2GHG is the Hadley Center data for 2050-2059 from the greenhouse gas only run GCM output.

[c] HadCM2SUL is the Hadley Center data for 2050-2059 from the greenhouse gas and sulphate run GCM output.

[d] Where E-IL is eastern Illinois, EC-IN is east-central Indiana, NW-OH is north-west Ohio, SC-MI is south-central Michigan, S-ILis southern Illinois, SW-IN is south-west Indiana, E-WI is eastern Wisconsin, SW-WI is south-west Wisconsin, W-IL is western Illinois, and MI-Th is the Michigan thumb.

Table 3: Mean maximum decadal yield planting dates (Julian days) under VEMAP current climate and future HadCM2GHG (halved variability (0.5) / unchanged variability (1.0) / doubled variability (2.0)) and HadCM2SUL (halved variability (0.5) / unchanged variability (1.0) / doubled variability (2.0)) climate scenarios for maize varieties

Site[a]	VEMAP[b]	HadCM2GHG[c]			HadCM2SUL[d]		
		0.5	**1.0**	**2.0**	**0.5**	**1.0**	**2.0**
E-IL :LSC[e]	130 (260[h])	186 (204)	186 (212)	179 (173)	179 (227)	186 (223)	179 (210)
:MSC[f]	158 (261)	207 (218)	207 (185)	74 (165)	193 (215)	200 (194)	81 (178)
:SSC[g]	179 (235)	195 (132)	207 (138)	218 (125)	200 (159)	207 (147)	200 (139)
EC-IN:LSC	123 (252)	186 (215)	179 (196)	158 (181)	172 (218)	172 (221)	158 (200)
:MSC	144 (272)	193 (234)	200 (201)	144 (218)	186 (255)	186 (212)	172 (248)
:SSC	158 (208)	144 (136)	207 (127)	151 (122)	207 (164)	207 (138)	144 (148)
NW-OH:LSC	116 (241)	179 (224)	172 (218)	165 (213)	158 (243)	158 (228)	144 (217)
:MSC	123 (267)	179 (262)	179 (205)	165 (268)	172 (312)	172 (217)	144 (292)
:SSC	158 (198)	137 (176)	137 (151)	165 (157)	172 (190)	172 (164)	158 (181)
SC-MI :LSC	137 (212)	165 (220)	172 (219)	114 (208)	137 (236)	151 (235)	144 (227)
:MSC	137 (274)	179 (272)	186 (222)	144 (269)	165 (303)	172 (232)	151 (299)
:SSC	158 (208)	130 (169)	137 (156)	151 (171)	165 (182)	172 (177)	172 (184)
S-IL :LSC	151 (258)	200 (219)	186 (199)	193 (176)	186 (234)	186 (207)	186 (198)
:MSC	165 (258)	207 (181)	207 (167)	81 (160)	200 (215)	200 (195)	200 (174)
:SSC	179 (195)	130 (124)	102 (118)	130 (121)	207 (136)	207 (126)	116 (124)
SW-IN :LSC	151 (256)	186 (247)	186 (218)	186 (218)	179 (246)	165 (230)	172 (217)
:MSC	165 (255)	200 (232)	207 (207)	200 (192)	193 (250)	193 (209)	193 (212)
:SSC	151 (201)	207 (167)	207 (143)	207 (144)	207 (194)	207 (162)	200 (158)
E-WI :LSC	123 (184)	179 (233)	158 (190)	172 (196)	165 (243)	151 (223)	151 (218)
:MSC	144 (252)	193 (265)	193 (189)	186 (238)	186 (299)	172 (214)	172 (280)
:SSC	158 (224)	193 (151)	144 (145)	179 (140)	193 (190)	179 (162)	186 (168)
SW-WI :LSC	123 (213)	172 (214)	179 (205)	172 (192)	165 (234)	158 (228)	144 (215)
:MSC	151 (272)	186 (264)	193 (200)	186 (232)	179 (284)	179 (217)	165 (277)
:SSC	165 (233)	193 (155)	207 (139)	186 (139)	207 (174)	186 (172)	172 (174)

W-IL :LSC	137 (261)	74 (168)	186 (166)	74 (150)	179 (199)	186 (216)	88 (165)
:MSC	137 (219)	81 (179)	102 (149)	81 (155)	74 (188)	200 (180)	81 (185)
:SSC	137 (122)	109 (150)	102 (112)	109 (117)	95 (164)	109 (130)	116 (140)
MI-Th :LSC	137 (171)	179 (242)	165 (218)	158 (212)	151 (240)	130 (215)	158 (220)
:MSC	137 (269)	186 (300)	179 (207)	179 (262)	179 (307)	151 (213)	158 (286)
:SSC	137 (209)	200 (176)	200 (163)	193 (162)	193 (192)	186 (171)	186 (168)

[a] Where E-IL is eastern Illinois, EC-IN is east-central Indiana, NW-OH is north-west Ohio, SC-MI is south-central Michigan, S-IL is southern Illinois, SW-IN is south-west Indiana, E-WI is eastern Wisconsin, SW-WI is south-west Wisconsin, W-IL is western Illinois, and MI-Th is the Michigan thumb

[b] VEMAP dataset for current climate data.

[c] HadCM2GHG is the Hadley Center data for 2050-2059 from the greenhouse gas only run.

[d] HadCM2SUL is the Hadley Center data for 2050-2059 from the greenhouse gas and sulphate run.

[e] LSC is long-season maize

[f] MSC is medium-season maize

[g] SSC is short-season maize

[h] Maize yields are given in bu/ac

Table 4: Number of days in the growing season (1 May – 30 September) with maximum daily temperatures 35.0°-39.9° C, and 40.0°-44.9° C under VEMAP current climate and future HadCM2GHG (halved variability (**0.5**) /unchanged variability (**1.0**) /doubled variability (**2.0**)) and HadCM2SUL (halved variability (**0.5**) /unchanged variability (**1.0**) /doubled variability (**2.0**)) climate scenarios for the year 2055.

	VEMAP[a]		HadCM2GHG[b]: 2055						HadCM2SUL[c]: 2055					
Site[d]	Max. Temp >35°C	Max. Temp >40°C	Max. Temp >35 °C			Max. Temp >40 °C			Max. Temp >35 °C			Max. Temp >40 °C		
			0.5	**1.0**	**2.0**	**0.5**	**1.0**	**2.0**	**0.5**	**1.0**	**2.0**	**0.5**	**1.0**	**2.0**
E-IL	5	0	92	80	95	13	28	28	44	45	37	0	5	0
EC-IN	1	0	62	69	56	6	9	3	12	18	14	0	0	0
NW-OH	1	0	20	34	35	0	1	1	6	5	6	0	0	0
SC-MI	0	0	15	12	10	0	0	0	2	2	0	0	0	0
S-IL	9	0	89	83	93	22	28	30	32	44	44	0	1	0
SW-IN	4	0	60	65	69	4	9	7	8	17	19	0	0	0
E-WI	0	0	43	35	44	1	4	0	2	4	4	0	0	0
SW-WI	0	0	55	48	45	1	3	2	1	7	1	0	0	0
W-IL	3	0	87	80	91	30	28	39	44	45	47	0	5	0
MI-Th	0	0	15	16	22	0	1	0	0	1	0	0	0	0

[a] VEMAP dataset for current climate data.

[b] HadCM2GHG is the Hadley Center data for 2050-2059 from the greenhouse gas only run.

[c] HadCM2SUL is the Hadley Center data for 2050-2059 from the greenhouse gas and sulphate run.

[d] Where E-IL is eastern Illinois, EC-IN is east-central Indiana, NW-OH is north-west Ohio, SC-MI is south-central Michigan, S-IL is southern Illinois, SW-IN is south-west Indiana, E-WI is eastern Wisconsin, SW-WI is south-west Wisconsin, W-IL is western Illinois, and MI-Th is the Michigan thumb.

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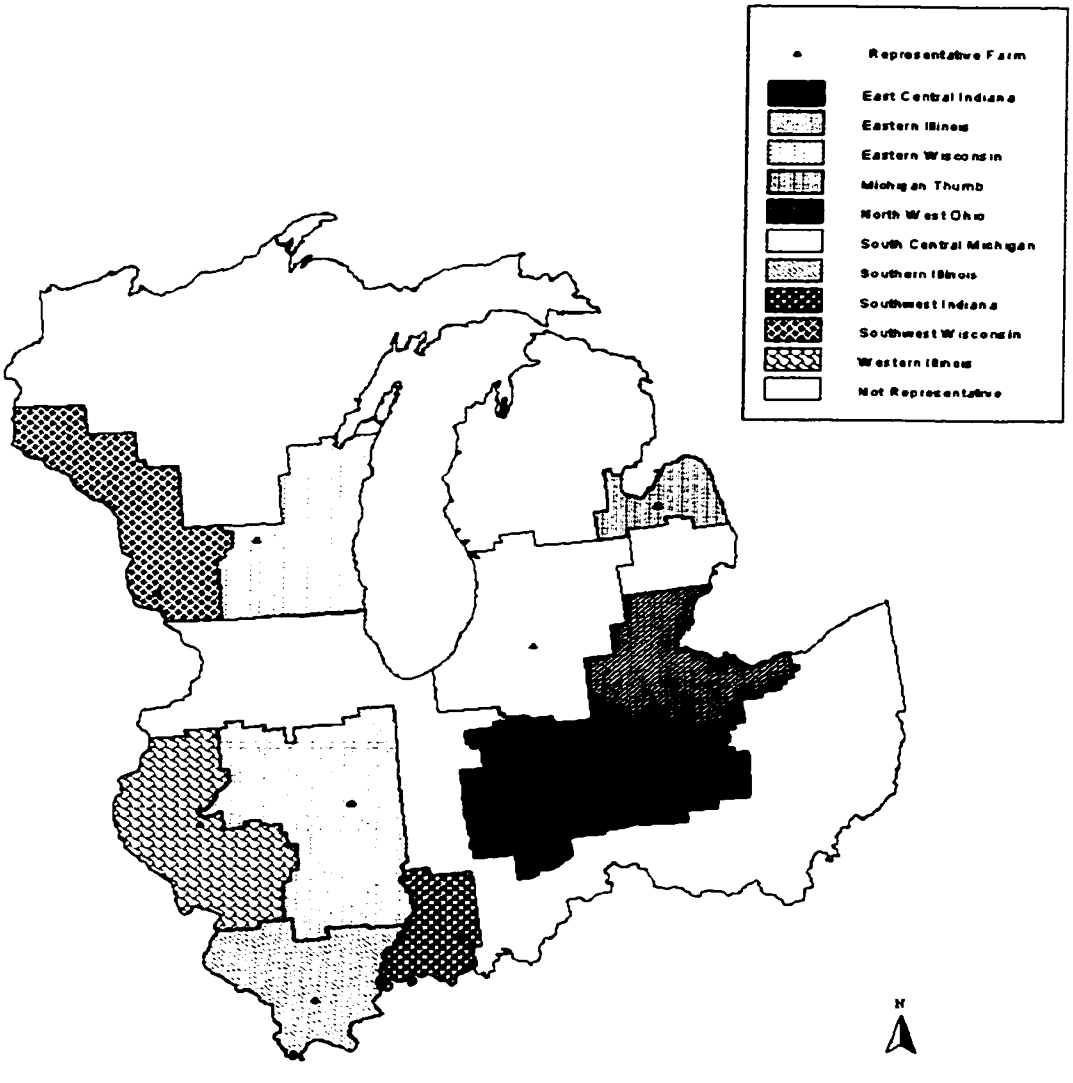
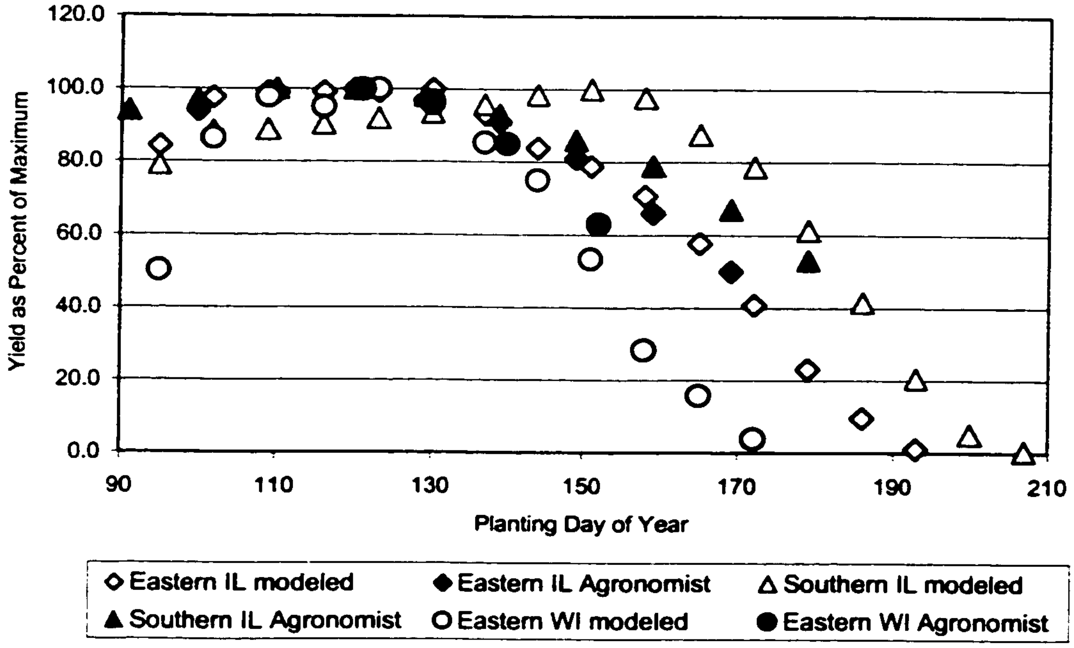
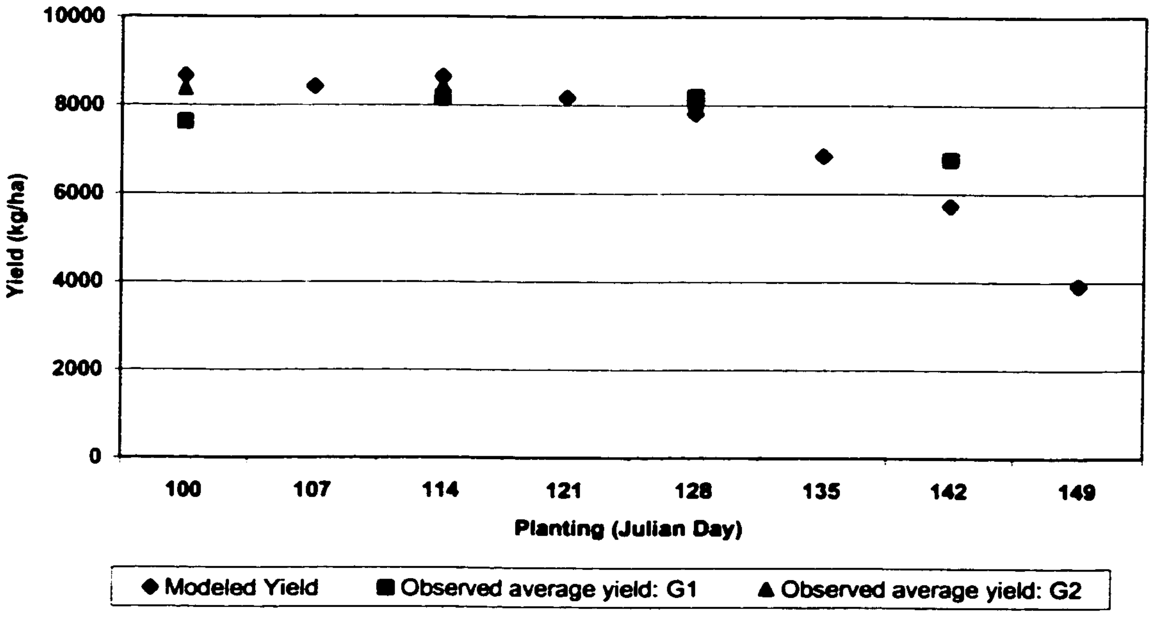

Representative Farm
East Central Indiana
Eastern Illinois
Eastern Wisconsin
Michigan Thumb
North West Ohio
South Central Michigan
Southern Illinois
Southwest Indiana
Southwest Wisconsin
Western Illinois
Not Representative
N

(a)

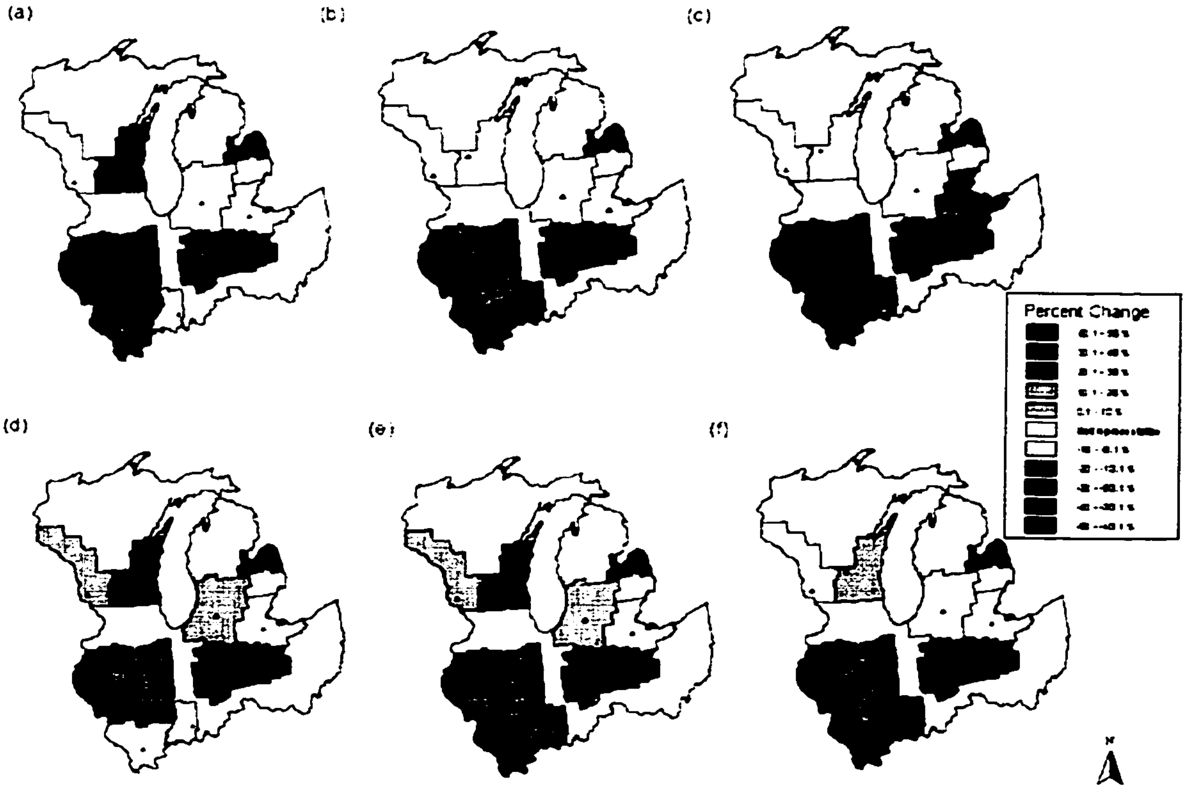


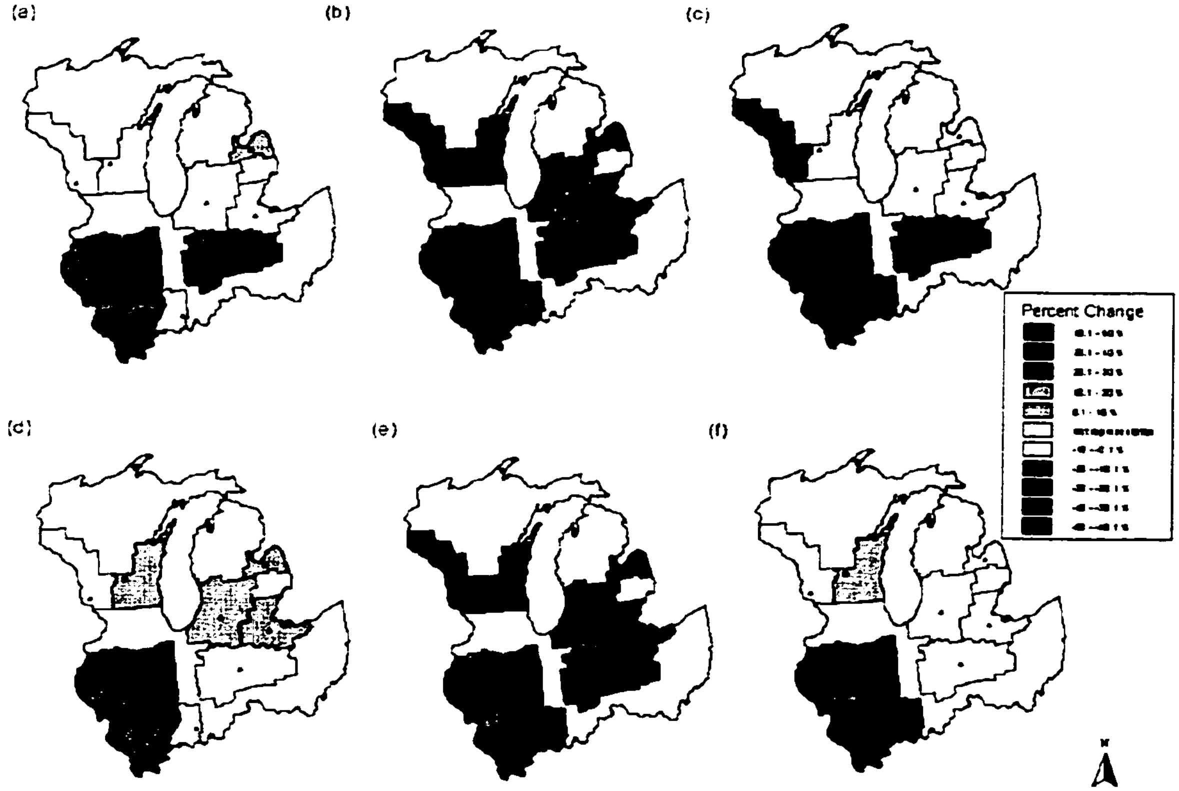
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Yield as Percent of Maximum
90
110
130
150
170
190
210
Planting Day of Year
◇ Eastern IL modeled
◆ Eastern IL Agronomist
△ Southern IL modeled
▲ Southern IL Agronomist
○ Eastern WI modeled
● Eastern WI Agronomist

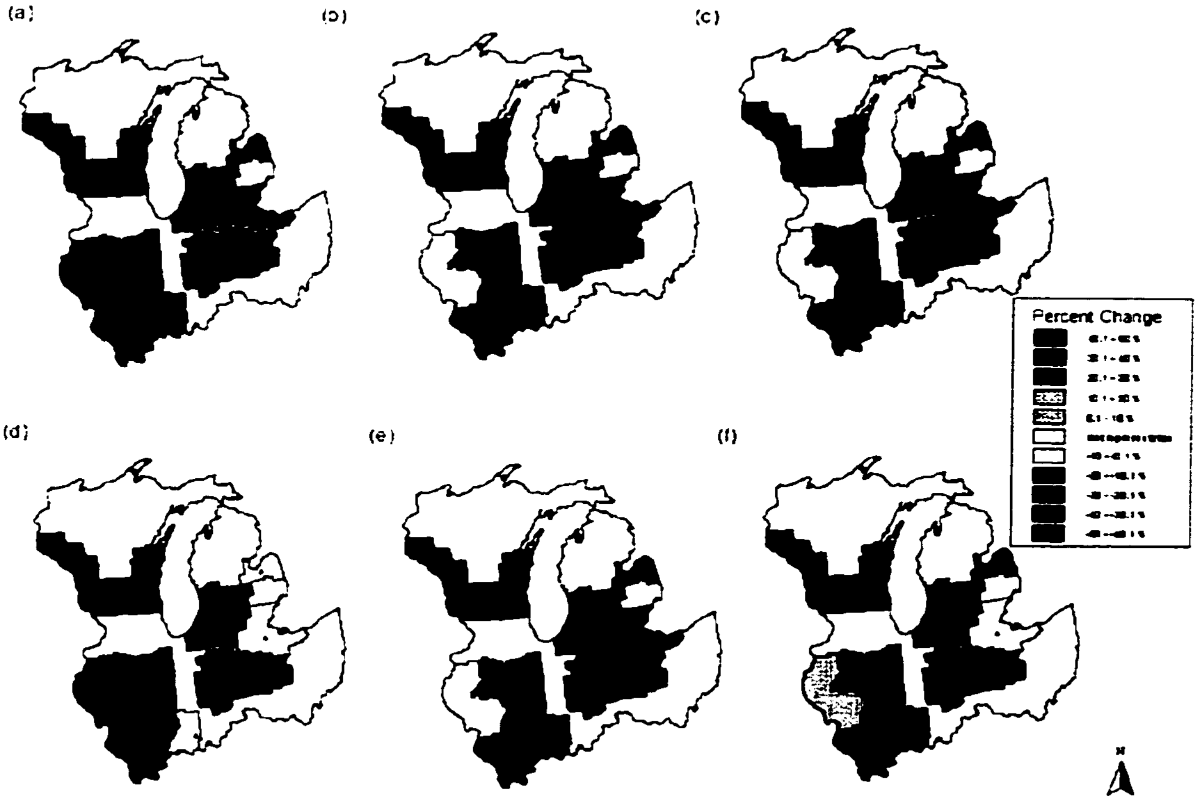
(b)

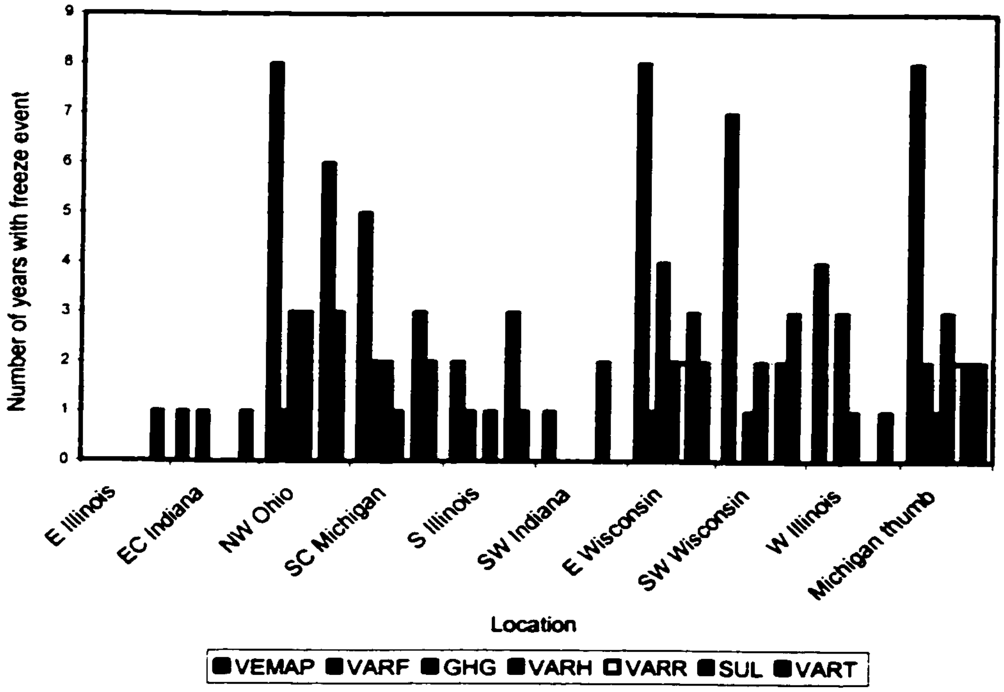


10000
8000
6000
4000
2000
0
Yield (kg/ha)
100
107
114
121
128
135
142
149
Planting (Julian Day)
◆ Modeled Yield
■ Observed average yield: G1
▲ Observed average yield: G2


(a)
(b)
(c)
(d)
(e)
(f)
Percent Change
N


(a)
(b)
(c)
Percent Change
(d)
(e)
(f)
N


(a)
(b)
(c)
(d)
(e)
(f)
Percent Change
N


Number of years with freeze event
0
1
2
3
4
5
6
7
8
9
E Illinois
EC Indiana
NW Ohio
SC Michigan
S Illinois
SW Indiana
E Wisconsin
SW Wisconsin
W Illinois
Michigan thumb
Location
■VEMAP ■VARF ■GHG ■VARH □VARR ■SUL ■VART

Chapter 4:

An integrated GIS and modeling approach for assessing the transient response of forests of the Southern Great Lakes region to a doubled CO_2 climate.

In Press: *Forest Ecology and Management*

Ehman, Jeffrey L., Weihong Fan, J.C. Randolph, Jane Southworth, and Nicole Turrill Welch

Abstract

This research examines the effects of climate change on the species composition of forests in the southern Great Lakes region (Illinois, Indiana, and Ohio) by simultaneously addressing five key components necessary for realistic predictions of future forest composition. We simulated transient species-level forest response to climate change at a spatial scale that accounted for competitive effects and regional site diversity in the spatial configuration of forests within the regional landuse matrix. The JABOWA-II forest growth model was used to provide species-specific responses of 45 tree species to site conditions (e.g., climatic, edaphic) while accounting for competition for limited resources (e.g., light, nutrients, water). Forest growth was simulated annually from 1981 to 2060 in 0.01 ha plots, each representing a unique 4-km^2 area (site) in the region with 30% or more forest cover (16,431 unique sites). Geo-spatial input data included land use (Land Use/Land Cover Data), community-level tree species composition (Eastwide Forest Inventory Database), site conditions (State Soils Geographic Data Base, Digital Elevation Model), baseline climate (1951-1980 normals from National Oceanic and Atmospheric Administration weather stations), and general circulation model output for generating the changed climate scenario (2 x CO_2 equilibrium run, Oregon State

University model). The equilibrium run output, which predicted temperature increases ranging from 3.11 to 3.67 °C and precipitation increases from 2 to 14% over the study area, was applied linearly to the baseline climate over an eighty-year modeling period. Results from forty iterations of simulated forest growth under each climate scenario (baseline and changed) were compiled at ten-year intervals as total basal area for each species. These plot results were scaled to the appropriate site according to the amount of forest cover in the 4-km^2 areas. Dominance-weighted population centroids were calculated for the regional distribution of each species for both climate scenarios at the years 1981 and 2060. Relative to forest conditions at 2060 after growth under baseline climate, the climate change scenario caused a decrease in total basal area of northern conifers (-99.9%) and northern deciduous (-99.4%) species and only a slight increase in intermediate (+1.23%) and southern species (+0.3%). Direction of population centroid shifts for these four species groups primarily were northeast. Our results for the northern species groups were consistent with previous studies. Possibly, our most important results were the minor differences in relative response for intermediate and southern species at the group level.

Keywords: climate change, forest dynamics, gap model, GIS (Geographic Information Systems)

1.0 Introduction

Predicting future regional forest structure under a changed climate requires realistic scenarios of future climate, an understanding of how species respond to climate change, and a means of modeling those responses. The objective of this study was to examine the possible responses of trees species in the southern Great Lakes Region (Illinois, Indiana, and Ohio) to a 2 x CO_2-changed climate scenario. More specifically, we wanted to assess future forest structure by "growing" forest plots consisting of real forest trees under real site conditions as climate changed until a point in time at which 2 x CO_2-induced conditions were realized. These "transient" responses are arrived at through a method distinctly different from that used to gauge "equilibrium" response, in which plot growth is simulated for an arbitrary time period (usually > 300 years) under fully altered conditions until an equilibrium forest structure is reached.

This region presents several challenges in meeting the three prediction requirements while conducting an analysis of this type. First, forests in this region occur within a highly altered landscape matrix (Figure 1). Second, the region's forests are composed of a relatively large number of dominant species, all with unique life histories, growth characteristics, and climatic tolerances. Third, these species are subject to a wide range of climatic conditions within the region, due to its continental position. Fourth, the forests are situated across varying soil, nutrient, and topographic gradients. Our task was to simultaneously consider these forest properties and exogenous conditions at the appropriate spatial and temporal scales. Malanson (1993), Dale and Rauscher (1994), and Loehle and LeBlanc (1996) present critical analyses of previous approaches used to model forest response to climate change for this and other regions.

Long-term variability in temperature, precipitation, and other climatic conditions is a natural part of our climate system. However, anthropogenically increased concentration of carbon dioxide (CO_2) in the atmosphere has led to international concern about the potential for dramatic climate change over the next century and beyond (Houghton et al. 1996, Kienast et al. 1996). Future climate change predictions vary but certain trends are evident across most general circulation models (GCM). Similar output results both from equilibrium GCM runs at doubled atmospheric CO_2 (e.g., Oregon State University model, OSU) and transient runs (e.g., the Hadley Center Model, HADCM2, or the Canadian Climate Model, CGCM1) for the year 2060. These models generally predict a warmer, moister climate with increases in annual average global temperature ranging from 2.5° to 5.0° C and increases in annual average global precipitation ranging from 4% to 9% (Schlesinger and Zhao 1988, Doherty and Mearns 1999).

Species respond to climate change in an individualistic manner. Paleoecological studies of Holocene forests reveal that forest communities do not respond as units (Davis 1981, Webb 1987, Huntley 1991). Rather, new species assemblages form and reform as each species responds to climate change. Characteristics such as competitive ability and seed dispersal mechanisms are critical to determining regional shifts in dominance (Davis 1986, Webb 1986, Malanson 1993), particularly when climate change is studied on time scales of 10,000 years or less (Solomon et al. 1981, Solomon and Webb 1985). Adjustment to a new physical environment depends upon the environmental tolerance ranges of the species. Species might flourish under the new climatic conditions, migrate into a new region, or be extirpated in a given region (Randolph and Lee 1994). Such individualistic responses necessitate a species based model if analysis at the species-level is desired.

One group of models commonly used to predict forest response to climate change is the community vegetation dynamics model, often referred to as gap models. Most are derived from the JABOWA-FORET lineage (Botkin et al. 1972, Shugart and West 1977). Gap models simulate forest dynamics on a small spatial scale (here 0.01 ha) with competition among individual trees for limited resources. Botkin (1993) found that the JABOWA model realistically and accurately simulated forest growth in both the short- (1-25 years) and mid-term (50-70 years). Gap models retain the individualism considered necessary for predicting forest response to short-term climate change; however, they are most often applied at a local scale and then extrapolated to a regional-scale to examine regional level forest responses (Botkin et al. 1989, Urban and Shugart 1989). Such scaling techniques might not always provide accurate results at a regional level, especially where local-scale site or tree species diversity could significantly influence results.

To simulate local-scale forest growth for many individual forested areas across a large region, a geographic information system (GIS) is helpful. Most gap models require input files that contain the set of individual trees, physiological characteristics of each species present or potentially inhabiting the site, growing conditions at the site, and climatic conditions for each modeled forest site. Manipulation of these spatial databases is required to maintain realistic local-scale spatial variability of the forest site characteristics across a region. A GIS is well suited to this task, as well as in efficient storage, retrieval, analysis, and display of site-specific model results.

Global climate change is expected to affect the growth and distribution of forests at several spatial and temporal scales (Graham et al. 1990, Randolph and Lee 1994, Loehle and LeBlanc 1996, Schenk 1996, Lindner et al. 1997). Some of the most adverse impacts of future climate change are projected to occur in the Midwest and Great Plains regions (Loehle and LeBlanc 1996). Of the few studies that predict forest response to climate change for these areas, none have overcome all of the challenges presented above. Our study simulated these responses over a relatively broad spatial scale, the three-state region of Ohio, Indiana, and Illinois, but with a spatial, temporal, and taxonomic resolution consistent with the assessment needs described above. The temporal scale (80 years) was constrained by the point in time (2060 A.D.) near which atmospheric CO_2 concentration is expected to double pre-industrial levels (Houghton et al. 1996), and by which a forest response is expected (Urban and Shugart 1989). Our simulation period is consistent with that used by other researchers (Botkin et al. 1989, Urban and Shugart 1989) who used gap models to predict transient forest response to climatic change. We imbedded JABOWA-II (Botkin 1993) within a GIS to facilitate our analysis of the temporal and spatial changes in total basal area and regional population centers for the tree species of the region in response to a changed climate, with respect to forest growth under baseline climate conditions.

2.0 Methods

2.1 Study region

The southern Great Lakes region comprises Illinois, Indiana, and Ohio. The maximum extent of ice sheets during the most recent glaciations, 18,000-20,000 years before present, covered the northern two-thirds of the study region. Forested land is found primarily in unglaciated uplands of the Ohio River Valley, and along larger rivers and creeks in glaciated areas now dominated by agriculture (Figure 1). Oak-hickory, beech-maple, and other mixed mesophytic associations (including such tree species as hackberry, red maple, tulip polar, basswood and elm) dominate the forested areas (Barrett

1995, Hicks 1998). Oak-hickory forests generally are found on Ultisols and Mollisols, beech-maple forests on Alfisols, and mixed mesophytic forests on Inceptisols and Ultisols (USGS 1970, Hicks 1998).

Forests of this region are subject to a humid continental climate, which is characterized by extreme events including cold waves, heat waves, blizzards, floods or droughts. Both winter and summer temperatures are severe, resulting in large annual temperature ranges. July means are from the low 20s (°C) in the northern most areas of these states to the mid to high 20s in the southern regions. In winter the temperature gradient from north to south is stronger than in warm months and values range from –10s in the north to single digits in the south. Annual temperature ranges generally increase from north to south and from west to east across these three states. Precipitation follows a similar pattern with a decrease in precipitation from east to west as well as from south to north, with a range of 80-200 cm per year, primarily due to the increasing distance from the Gulf of Mexico, the source of warm, moist tropical air (Lutgens and Tarbuck 1995). Locations near the Great Lakes have greater annual precipitation amounts.

2.2 *Analytical approach*

We evaluated the spatial distribution of forests within the study area by overlaying a grid of the region (4-km^2 resolution) with Land Use/Land Cover Data (LULC) produced by the USGS (1990). All 4-km^2 cells with 30% areal coverage by Level 1 "Forested Lands" (Anderson et al. 1976) were used to produce a basemap with 16,431 forested cells (Figure 2). Forested wetlands, which comprise less than 3% of forested land in the study area, were not included in the analysis due to problems with providing adequate site-level model inputs (i.e., available nitrogen levels).

Forest composition was obtained from the Eastwide Forest Inventory Data Base (EWDB) produced by the USDA Forest Service (Hansen et al. 1992). These data include species name and diameter at breast height for 158,589 measured trees from 5019 forested survey plots across the three-state region. These 5019 survey plots were selected based on their locations within the 4-km^2 grid cells which had at least 30% areal coverage of forest. All EWDB plot locations occurring within these selected cells were used in this analysis. Forty-five of a possible 167 tree species in the EWDB were selected for inclusion in the simulation based on dominance in the region. These selected species were grouped into four categories: "Northern Conifers," "Northern Deciduous," "Intermediate," and "Southern," based upon their climatic tolerances and breadth of latitudinal range (Küchler 1970, Little 1971, 1976) (Table 1). Individuals of a particular species were included in these simulations wherever EWDB records reflected their presence. JABOWA-II (Botkin 1993) simulated forest growth at annual time steps within 16,431 plots, each 0.01 ha plot representing a different 400-ha (2 km x 2 km) forested cell (site) within the three-state region. Average results were derived from forty iterations of the eighty-year simulation, for each forest site.

2.3 Model inputs

JABOWA-II required species, stand, climate, and site files as inputs (Figure 2). Stand, climate, and site files were site-specific. Species files were created uniquely for each county.

2.3.1 Stand file

The stand file for each forested cell was generated from the EWDB. Data recorded at the survey plot within or nearest the simulated 4 km^2 cell were used, which allowed baseline stand conditions to be generated with high spatial specificity. We assumed the EWDB adequately sampled forested uplands of the study region.

2.3.2 Species file

Physiological and life history parameters specific to 45 tree species (Burns and Honkala 1990) were used in the simulations. These were used to modify the original growth parameter files provided in the JABOWA-II model (Botkin 1993). Two of these parameters, minimum and maximum growing degree-days, are used to define a thermal response curve which is used to estimate tree growth increment. Following Botkin (1993), we assigned species' degree-days tolerances on the basis of present continental range (Little 1971, 1976).

The ubiquitous dispersal assumption implicit in JABOWA-II, and other gap models (Hanson et al. 1990), limits establishment of new individuals (i.e., recruitment of seedlings) in the plot during a simulation to the set of tree species listed in the species file. We included those species present in a given county and all adjacent counties at baseline conditions in county-specific species files. Hence, species migration was constrained at county-scale, consistent with the dispersal rates realized by most species during the Holocene (Davis 1989).

2.3.3 Climate files

Data from 1180 National Oceanic and Atmospheric Administration (NOAA) weather stations in and around the study region were spatially interpolated to provide continuous coverage of average monthly temperature and precipitation from 30-year normals (1951-1980). To generate files representing 2 x CO_2 induced climate conditions, output from an equilibrium run of the OSU GCM was applied to the 30-year normals.

The GCM was selected because of 1) its compatibility with the 1995 Intergovernmental Panel on Climate Change (Houghton et al. 1996) projections and 2) its results for the Midwest are similar to those obtained from the most current transient model runs for 2060 (Doherty and Mearns 1999). Delta values were added step-wise to the 30-year normals to create a linear warming ramp (Solomon 1986, Pastor and Post 1988) for the 80-year modeling period (1981 to 2060). We assumed that 2 x CO_2 equilibrium conditions were realized by the year 2060, and that transient changes in temperature and precipitation will occur linearly.

2.3.4 Site files

Site files specific to each of the 16,431 forested cells included topographic and edaphic characteristics (Table 2). Site files were generated from the average conditions existing in each 4 km^2 cell. Among site factors, accurate parameterization for available nitrogen (AVAILN) was important because of 1) its role as a limiting nutrient in forests of this study area (Hicks 1998) and 2) JABOWA-II's sensitivity to this variable (Botkin 1993). AVAILN values assigned to each cell were determined with the NM-model developed by Fan et al. (1998), which predicts available nitrogen as a function of climate, litter quality, and soil texture, as determined from independent data sets for the study region. Because the JABOWA-II model does not simulate nutrient dynamics, site-specific available nitrogen levels remained static throughout the modeling period.

2.4 Model output

JABOWA-II output for each climate scenario was compiled at ten-year intervals as total basal area for each species existing at each modeled 0.01-ha plot. After calculating averages from the 40 iterations of simulated forest growth, results for the years 1981 and 2060 were related to the appropriate 4 km^2 cell in the forest matrix database (Figure 2). Species' average total basal area at each plot was scaled to the cell (site) based on the proportion of LULC forest cover (30-100%) within the respective cell.

Evaluating the impact of climate change necessitates a comparison to what would have occurred without the change in climate (Urban and Shugart 1989, Botkin et al. 1989). With this caveat, we analyzed model output in three ways. First, non-spatially specific responses to the changed climate with respect to baseline conditions were defined for each species as:

$$100 * (\text{total basal area}_{\text{changed}} - \text{total basal area}_{\text{baseline}}) / \text{total basal area}_{\text{baseline}},$$

at the year 2060. Second, basal area-weighted population centers, or centroids (Shyrock 1980), were calculated to investigate the temporal changes in the distribution of each species' population. The impact of climate change was defined as the difference between the year 2060 centroids of the two scenarios. This novel application of centroids allowed us to quantify the direction and distance of change by representing the shifts in species' ranges as vectors linking centroids from the two different climate scenarios. Third, choropleth thematic maps were produced for species groups and regionally-dominant species to assess the complete spatial pattern of growth response, and impact (through visual comparison of the two 2060 conditions). The amount of spatial information precluded its full presentation for all species.

2.5 *Model limitations*

Several properties of the JABOWA-II model should be critically evaluated. First, the temperature-growth equations are defined as uniform parabolas with endpoints derived from conditions existing at present day range limits of each species. Thus, optimal growth will occur halfway between the extremes, where responses are especially sensitive, and asymmetrical or multimodal responses are not considered (Malanson 1993).

Second, species' continental ranges used to assign thermal tolerance were considered to be in equilibrium with the current climate. Thus, the realized species ranges equal the fundamental species ranges (Loehle and LeBlanc 1996). However, tree species are continually adapting to a continually changing climate (Davis 1986) and present range limits can be a function of competition rather than climatic tolerance (Malanson 1993).

Third, the JABOWA-II model linearly relates moisture to growth as the number of drought-days during the growing season. Where drought significantly retards growth, e.g., in a non-linear fashion, this sub-model could produce erroneous results (Malanson 1993).

Fourth, the model assumes that all individuals of a species are genetically identical. In reality, considerable genetic variability exists within these species, which at the range margins might be critical to population survival during climatic change.

Fifth, JABOWA-II assumes that available nitrogen remains static throughout the simulation. While largely dictated by soil characteristics, changes in climate, atmospheric deposition, species composition, and/or alteration of microbial communities, could alter this model parameter.

Although the JABOWA-II model incorporates these assumptions and thus, presents some limitations to the interpretation of results, it is well suited for our purposes.

A number of models were considered because we desired to incorporate an existing forest growth model rather than to create a new one.

3.0 Results

3.1 Regional changes in total basal area

Response to the baseline and changed climate scenarios, and the difference in response between the two (i.e., the impact of climate change), are presented at the species- and species group-level in Table 1. At the beginning of the simulation in 1981, Northern Conifers, Northern Deciduous, Intermediate and Southern species comprised 0.8, 9.5, 75.7, and 14.1%, respectively, of the total basal area of the region. Considering all species combined, total basal area of the region increased 61.9% under baseline climate conditions from 1981 to 2060. Under changed climate conditions, total basal area increased 49.2% from 1981 to 2060. The effect of climate change on the overall species composition with respect to baseline conditions was a 7.9% decrease in total basal area.

The effect of climate change on Northern Conifers and Northern Deciduous species was an overall decrease in total basal area for the region. Under baseline climate, there was an 8.8% increase in total basal area of Northern Conifers by 2060. However, under changed climate conditions, the total basal area of Northern Conifers decreased by 99.9% over the 80-year period. Under baseline and changed climate conditions, there was a 43.8% increase, and a 99.1% decrease, respectively, in total basal area of Northern Deciduous species.

The total basal area of Intermediate and Southern species increased only slightly under the effects of climate change, relative to baseline. Under baseline climate, there was a 72.4 and 20.4% increase in total basal area of Intermediate and Southern species, respectively. Under changed climate conditions, total basal area of Intermediate species increased by 74.5% and total basal area of Southern species increased by 20.7%. The effect of climate change with respect to baseline conditions on Intermediate species was small (1.2% increase) and the effect on Southern species was minimal (0.3% increase).

3.2 Shifts in regional population centroids

After 80 years of forest growth, Northern Conifer centroids shifted east-southeast under baseline conditions and northwestward under changed climate conditions (Figure 3a). The distance between the baseline and changed climate centroids at 2060 was 252.6 km. The population centers of Northern Deciduous species under baseline climate conditions shifted slightly eastward (Figure 3b). The shifts to the north and east under changed climate conditions gave rise to a difference of 140.2 km for year 2060 centroids for Northern Deciduous species.

Under baseline and changed climate conditions, the population centroids of Intermediate species changed only slightly over the 80 years of growth (Figure 3c). The impact of climate change was negligible in terms of directional shifts: 22.4 km to the east. Southern species under changed climate conditions moved slightly northeastward, resulting in a minor (32.0 km) centroid shift (Figure 3d).

3.3 Shifts in regionally dominant species

Five of the 45 species included in the simulation accounted for 55.1% of the total basal area of the study region forests. Those species were white oak (Quercus alba) (19.2%), black oak (Q. velutina) (12.5%), northern red oak (Q. rubra) (10.4%), sugar maple (Acer saccharum) (7.4%), and American beech (Fagus grandifolia) (5.6%).

Pignut hickory (Carya glabra) accounted for 2.0% of the total basal area of the study region.

The population centroid for white oak (Figure 4a) and pignut hickory (Figure 4b) remained stationary after eighty years of baseline conditions. The population centroid of black oak (Figure 4c) moved slightly eastward and that of northern red oak (Figure 4d) shifted to the southwest under baseline conditions. Under changed climate conditions regional dominance centers of all of these species shifted eastward.

Regional dominance of sugar maple (Figure 4e) shifted eastward under baseline conditions whereas American beech (Figure 4f) shifted to the south. The population centroid of sugar maple showed a strong northeasterly shift under changed climate conditions and was virtually eliminated. The population centroid of American beech shifted to the northeast under changed climate conditions.

4.0 Discussion

4.1 Comparison with other regional results.

At a regional level, our results for Northern Conifer and Northern Deciduous species' populations are generally in agreement with previous studies: climate change either initiates a northward shift of current range, a decline in dominance, or complete extirpation (Zabinski and Davis 1989, Randolph and Lee 1994, He et al. 1999). Although species-level response varies considerably for the Intermediate and Southern Species, when aggregated to the group level, the effect of climate change relative to growth under baseline climate is minor. Here our results differ somewhat from that of other studies.

An obvious and potentially significant result from this analysis is the loss of Northern Conifers and Northern Deciduous species from the study region. Unlike Michigan and Wisconsin just north of the study region, Northern Conifers are uncommon in the southern Great Lakes region under present climate conditions. Indeed, only four species were included in this group in our model and the group comprised less than 1% of the region's species composition (Table 1). In contrast Northern Deciduous species comprised a much larger proportion of the baseline basal area, most of that attributable to sugar maple (7.4% of total for all species). Under changed climate conditions sugar maple, and thus the Northern Deciduous group, is virtually eliminated. Zabinski and Davis (1989) expected sugar maple to fare better than other species in their simulations due to its high dispersal capacity and, hence, faster adaptation of cohorts. However, results from their climate threshold (i.e., transfer function) model for 2090 A.D. are strikingly similar to ours. Under a Goddard Institute for Space Studies GCM 2 x CO_2 climate scenario, the southern range limit of sugar maple extends just south of the northern borders of Illinois, Indiana, and Ohio. Using the more severe General Fluid Dynamics Laboratory GCM output, sugar maple is completely extirpated from the southern Great Lakes region.

He et al. (1999) showed similar decreases in northern coniferous and some northern hardwood species of Wisconsin. They linked a process-based ecosystem model and a spatially explicit landscape model to examine forest species responses to CO_2-induced climate warming. Similar to results of our study, the biomass of red pine (Pinus resinosa), quaking aspen (Populus tremuloides) and big-toothed aspen (P. grandidentata) decreased under a 5 °C temperature increase (He et al., 1999). The authors speculated that these species might not be able to establish under warmer conditions.

Randolph and Lee (1994) reported community- and species-level responses of Midwestern forests under the OSU 2 x CO_2 changed climate scenario. Both the southern mixed forests and the southern oak-hickory-pine forests expanded northward from their current ranges to areas formerly occupied by northern hardwood, beech-maple, elm-ash, mixed-mesophytic, Appalachian oaks, and northern and central oak-hickory forests. In turn, the ranges of these more northern forest types shifted to the north. When individual species were examined, the model predicted a loss of range for many northern hardwoods and most northern conifers.

A less dramatic and possibly less obvious but important result of our research was that, at the group-level, Intermediate and Southern species exhibited only a small response to the changed climate, relative to growth under baseline conditions. Considering that these two species groups represented 89.8% of the region's total basal area, more pronounced effects of climate change on these species would have caused greater changes in regional forest structure. Intermediate species with greater than 10% relative dominance, white oak and black oak, increased in basal area under the changed climate. The one exception to this was northern red oak, which decreased under both baseline and changed climate scenarios. Northern red oak is capable of growing on a wide variety of sites but tends to grow best on deep, well-drained soils of north facing slopes in this region (Hicks 1998). In drier conditions, northern red oak is often found with dry-adapted competitors such as chestnut oak (Quercus prinus), white oak, and black oak (Hicks 1998), all of which increased in total basal area under both climate scenarios in our study.

American beech increased in total basal area under both baseline and changed climate conditions (Table 1). American beech is a shade tolerant, slow growing, long-lived species (Burns and Honkala 1990, Hicks 1998). Zabinski and Davis (1989) proposed that for the Great Lakes region an increase in temperature would probably result in drier conditions due to increased evapotranspiration, so beech populations might be expected to decline. However, the absence of disturbance regimes in our simulations would favor an increase in species such as American beech (explained below). Persistence of beech is consistent with the response lags evident in the Holocene and expected in the future (Davis 1986, 1989). Longer (e.g., 300-year) simulations could reveal a response more in line with that proposed by Zabinski and Davis (1989).

Randolph and Lee (1994) used their species-level results to "reconstruct" probable forest communities. For southern Indiana, oak-hickory forest changed under OSU GCM equilibrium climate conditions to a southern mixed forest dominated by with southern red oak (Quercus falcata), post oak (Q. stellata), bur oak (Q. macrocarpa), and loblolly pine (Pinus taeda L.). While consistent with USEPA (1998) predictions, these results differ from ours (see Table 1). Moreover, it seemed anomalous that species adapted to dry site conditions, such as scarlet oak (Quercus coccinea), southern red oak, and Virginia pine (Pinus virginiana) (Hicks 1998), decreased under changed climate conditions. Such southern species are generally thought to be adapted to the increased temperature expected with climate change. One possible explanation is that these species are commonly found on poor quality sites (Hicks 1998). The majority of the forested areas of this region support growth rates and biomass levels that are relatively large in comparison to other areas of the eastern deciduous forest. In addition, the northward expansion of these species is limited by the extensive land use in intensive agriculture, across which migration will be difficult.

4.2 Analytical limitations

Our results should be interpreted within the context of the model assumptions, rather than as precise predictions of reality (Urban and Shugart 1989). To be of value for comparative purposes, or when future research is being designed, we believe it is necessary to 1) make explicit the limitations of our modeling approach, and 2) speculate on the possible changes in our results if certain assumptions were changed.

Houghton et al. (1996) predict linear temperature increases under constant 1990 aerosol conditions, but their "best estimate" scenario is slightly non-linear. Alternatively, stepped increases may occur. We speculate that while slight non-linearity in temperature ramping would have had limited influence on our results, the effect of rapid climate change pulses would have been more pronounced, at least within the 80-year simulations (Urban and Shugart 1989).

In addition to changes in mean climate conditions, intra-annual variability also will be a factor in shaping future forests. Current GCMs (e.g., HADCM2 or CGCM1) predict increased variability for major precipitation events (Shriner and Street 1998). However, including short-term variability may have had limited influence on our results. Like many other gap models, the annual growth increments allocated by JABOWA-II to trees are largely driven by monthly climate with variability constrained at that time scale. Hence, we believe that only longer-term or severe climatic episodes (e.g., multi-year drought) would have impacts on our results, which is consistent with the natural resistance for many of the species in this area (Burns and Honkala 1990).

The OSU GCM climate scenario assumes climate change effects resulting from doubled concentration of atmospheric CO_2. However, JABOWA-II, like most other gap models, does not have the ability to incorporate different concentrations of atmospheric CO_2. While some studies have shown increased growth in some tree species, particularly in seedlings, saplings and small trees (Norby et al. 1986), other studies have found variable responses among species (Bazzaz et al. 1990) and across age classes (Bazzaz and Williams 1991). Increased atmospheric CO_2 could increase growth rates of some species, particularly in smaller size classes; however, uniform growth rate increments due to CO_2 effects cannot be applied to all species and size classes. Consequently, the model did not make any adjustments for the direct effects of increased CO_2. When CO_2 effect was examined for IPCC (Shriner and Street 1998), a greatly reduced loss of leaf biomass resulted (0-7% decrease with the CO_2 effect versus a 12-76% decrease with no CO_2 effect).

Given that gap models often require 300 years or more of simulated forest growth to reach equilibrium with respect to species composition, it is likely that our results would change if simulations were extended temporally. Because our investigation of transient forest response was bounded at 2060, it is possible that our results reflect lags associated with species or community inertia (Davis 1986, 1989). If the time frame had been extended, we hypothesize that the Northern species groups would have been completely eliminated, and larger increases in the Southern Species would have been evident.

Alternatively, the limitations of our site files could have precluded inertia in our simulations. To some extent, spatial aggregation of site conditions within entire 4 km^2 cells precluded incorporation of the diversity of site conditions (i.e., microclimatic and edaphic) in the simulations. For example, in southern Indiana dendritic topography induces contrasting microclimates and accompanying tree species composition just meters apart. Under a future climate regime, increased temperatures could result in conditions too xeric for oaks and hickories. In this case, the cooler and more mesic northern slopes would likely host tree species presently associated with south-facing slopes and ridge crests. Also, we speculate that the Northern Deciduous group might persist in the most mesic and sheltered upland sites in the study region, not unlike relict Northern Conifer communities present today in southern part of our study region.

Natural and anthropogenic disturbance regimes were not included in these simulations. The effects of insects, fire, windthrow, soil fauna, and harvesting were not simulated. Two implications are noteworthy. First, the more shade-tolerant and longer-lived species would have a competitive advantage in our simulations over invasive species, which dominate larger forest openings after disturbance. This is evident in the large increase in total basal area of eastern hemlock (Tsuga canadensis) under baseline climate conditions (Table 1). Burns and Honkala (1990) name eastern hemlock as the most shade tolerant tree species in North America. Conversely, while other Intermediate species fare well under the baseline climate, early successional tree species such as sassafras (Sassafras albidum), black cherry (Prunus serotina), and red maple (Acer rubrum), incur basal area losses during the 80-year baseline climate simulation (Table 1). As expected, these three species fare better under the climate change scenario, presumably in plots where Northern Conifers and Northern Deciduous species die. Second, while the absence of disturbance allows an estimation of growth potential for these forests, the overall growth rates (61.9% for baseline climate) probably overestimate what would actually occur during the simulated period.

An important assumption in our analysis is that land use pattern and practices will follow current trends. In the northern part of our study region, agriculture has been the dominant land use for many years. Climate change could affect agricultural practices in this region by providing favorable opportunities for use of new cultivars and modifications in cropping practices, but the general pattern of conventional tillage agriculture is expected to persist in the same locations (Doering et al. 1997). The unglaciated southern part of the study region has thinner, less productive soils on more irregular terrain. There, forests are the dominant land use. Abandonment of former agricultural lands, re-growth of previously harvested forests and land acquisition by both state and federal forestry agencies has resulted in increased forested lands in the study region (Fischer 1998). The extent of urban and suburban land use has increased in all three states. Residential use of rural land is increasing with conversion of both agricultural and forested lands to residential and some commercial uses, particularly on the periphery of larger metropolitan areas. In sum, agricultural land use has declined, particularly in the southern part of the study region. We recognize that land use change could result in significant losses of private forests in this region, but know of no realistic way to model land use change through 2060 in a spatially explicit manner. However, if we assume that 1) the agricultural land base continues to decline, and 2) reforestation roughly balances deforestation per unit area in this region, then we speculate that a slight decrease in total basal area would result during the simulation period with respect to our predicted increases under both climate scenarios: deforestation will include mature forest, while reforestation involves smaller trees.

4.3 Implication for the study region

Because Northern Coniferous and Northern Deciduous species represent a small proportion of the region's species composition (10.3%), one might view the projected loss of these species as having limited ecological impact. However, as this shift could occur in a relatively short time, some understory woody and/or herbaceous species closely associated with the Northern Deciduous tree community also would probably disappear from the region if they could not adapt to conditions in the oak-hickory dominated forests. In general, associated species with lower genetic diversity might be less able to adapt and more prone to adverse impact (Woodman and Furiness 1989).

Furthermore, the loss of genetic biodiversity along range margins is noteworthy. We predict that large portions of the southern range of Northern species, including relict communities, would be regionally extirpated. While the assumption of genetic uniformity was implicit in our species files, and small pockets of some Northern species are predicted to persist through 2060, the loss of heat tolerant individuals of a species during a uniquely rapid climate change should be avoided. Collecting seeds from these southern provenances of Northern species would be advisable. Results of transfer function models could then be used in determining potential planting locations.

Due to the commercial value of several species in the Intermediate and Southern species groups, forest managers could view the possible changes in forest community composition positively. The dominance of such species (e.g., white oak, black oak, and pignut hickory) is predicted to increase, with decreases forecast for some less commercially viable (e.g., Northern) species. Here again, several assumptions would be necessary to predict the economic impacts related to our results. Only by using linked atmospheric, ecological, and economic models with dynamic land use sub-routines, which are current research needs (Shriner and Street 1998) not yet addressed, will a truly integrated assessment devoid of numerous assumptions be possible.

4.0 Conclusion

The high degree of site specificity included in this research allowed for greater local- and regional-scale realism relative to past efforts in modeling forest response to climate change for this region. This level of detail was possible by integrating the JABOWA-II model in a GIS. The highly-resolved geospatial data input to JABOWA-II produced results that coincided with that of other studies for some species groups and differed for others. In agreement with other studies, species at the southern limits of their ranges, the Northern Conifers and Northern Deciduous species, were almost completely extirpated from the study region. This result adds credibility to this specific prediction. In contrast, the effect of the changed climate on Intermediate and Southern species was negligible. If the spatial configuration of forests within the land use matrix had not been considered as with other studies, and if over 16,000 sites with actual trees had not been considered, these relatively warm-adapted species might have been found to expand their dominance northward by 2060.

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Table 1. Relative dominance (100* total basal area of a species / total basal area for all species) and effects of baseline and 2 x CO_2 climate change on the species of the southern Great Lakes region (Küchler 1970, Little 1971, 1976). Nomenclature follows Gleason and Cronquist (1991).

Tree Species by Species Groups	Relative dominance 1981 (%)	Change from 1981 to 2060 under baseline climate (%)	Change from 1981 to 2060 under changed climate (%)	Change between 2060 baseline climate and 2060 changed climate (%)
All Species	**100.00**	**61.90**	**49.17**	**-7.87**
Northern Coniferous Species	**0.76**	**8.75**	**-99.99**	**-99.99**
Pinus resinosa Aiton	0.09	-97.45	-100.00	-100.00
P. strobes L.	0.57	-93.90	-100.00	-100.00
P. sylvestris L.	0.04	-88.43	-100.00	-100.00
Tsuga canadensis Engelm.	0.07	1067.60	-99.85	-99.99
Northern Deciduous Species	**9.49**	**43.76**	**-99.14**	**-99.40**
Acer saccharum Marshall	7.43	11.70	-98.94	-99.05
Betula alleghaniensis Britton	0.00	-75.79	-100.00	-100.00
Fraxinus nigra Marshall	0.02	-96.65	-100.00	-100.00
Populus grandidentata Michx.	0.93	-87.79	-100.00	-100.00
P. tremuloides Michx.	0.05	-46.37	-100.00	-100.00
Tilia americana L.	1.14	366.28	-99.67	-99.93
Intermediate Species	**75.70**	**72.42**	**74.54**	**1.23**
Acer rubrum L.	4.60	-31.61	31.36	92.07
Acer saccharinum L.	2.66	234.93	246.34	3.41
Carya ovata (Miller) K. Koch	0.89	40.84	49.78	6.34
C. cordiformis (Wangenh.) K. Koch	1.88	414.56	-48.18	-89.93
Celtis occidentalis L.	0.81	872.12	-72.99	-97.22
Fagus grandifolia Ehrh.	5.68	100.80	150.22	24.61
Fraxinus americana L.	5.33	76.83	136.58	33.79
F. pennsylvanica Marshall	0.93	20.41	6.98	-11.16
Populus deltoides Marshall	2.64	90.31	124.13	17.77
Prunus serotina Ehrh.	3.42	-16.05	11.07	32.32
Quercus alba L.	19.37	36.96	54.95	13.13
Q. bicolor Willd.	0.39	-8.31	-90.23	-89.35
Q. macrocarpa Michx.	0.92	349.12	-31.62	-84.78

Q. rubra L.	10.45	-8.81	-13.63	-5.11
Q. velutina Lam.	12.59	20.98	70.90	41.26
Sassafras albidum (Nutt.) Nees	0.72	-70.89	-59.35	39.63
Ulmus americana L.	2.28	224.79	319.83	29.26
U. rubra Muhl.	0.74	909.01	818.59	-8.96
Southern Species	**14.05**	**20.41**	**20.72**	**0.26**
Juniperus virginiana L.	0.35	355.79	468.57	24.74
Pinus echinata Miller	0.29	70.15	103.15	19.39
P. virginiana Miller	0.14	24.32	-49.90	-59.70
Carya glabra (Miller) Sweet	1.99	-5.51	30.47	38.08
C. tomentosa (Poiret) Nutt.	0.69	-36.47	-9.19	42.94
Juglans nigra L.	1.99	25.29	77.19	41.43
Liquidambar styraciflua L.	0.42	-63.08	-52.17	29.55
Liriodendron tulipifera L.	2.55	30.75	49.30	14.19
Quercus coccinea Muenchh.	0.41	12.36	-31.83	-39.33
Q. falcata Michx.	0.24	-72.36	-47.30	90.68
Q. falcata var. pagodaefolia Raf.	0.12	-27.44	22.04	68.18
Q. imbricaria Michx.	0.50	20.48	-80.34	-83.68
Q. marilandica Muenchh.	0.05	-75.41	-52.29	94.00
Q. muehlenbergii Engelm.	1.00	-37.49	-21.85	25.03
Q. palustris Muenchh.	1.57	38.11	-91.48	-93.83
Q. prinus L.	0.92	102.66	39.86	-30.99
Q. stellata Wangenh.	0.95	-33.82	-9.93	36.11

Table 2: Site parameters influencing growth conditions.

Parameter	Units	Source (Citation)
Maximum basal area	$cm^2/100\ m^2$	EWDB (Hansen et al. 1992)
Elevation	M	DEM (USGS 1990b)
Soil depth	M	STATSGO (USDA 1994)
Rooting depth	M	STATSGO (USDA 1994)
Depth of water table	M	STATSGO (USDA 1994)
Moisture capacity	mm H_2O/mm depth	STATSGO (USDA 1994)
Rock in soil matrix	%	STATSGO (USDA 1994)
Available nitrogen	-100 to +100 (unitless)	NM Model (Fan et al. 1998)

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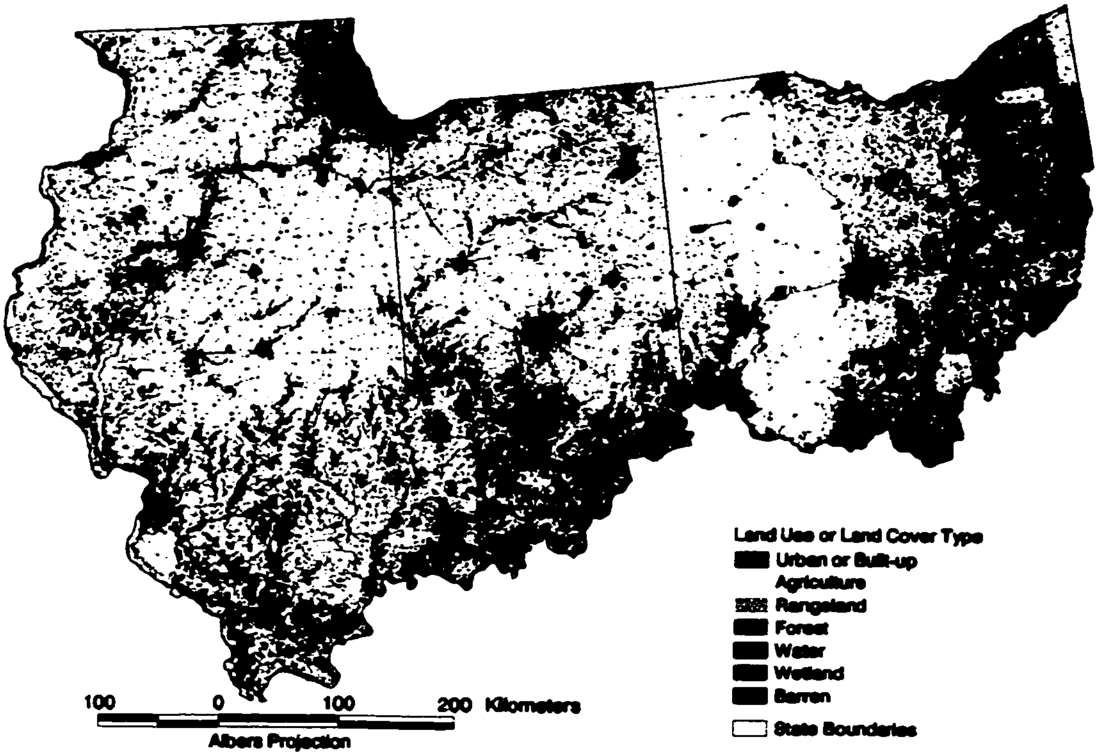
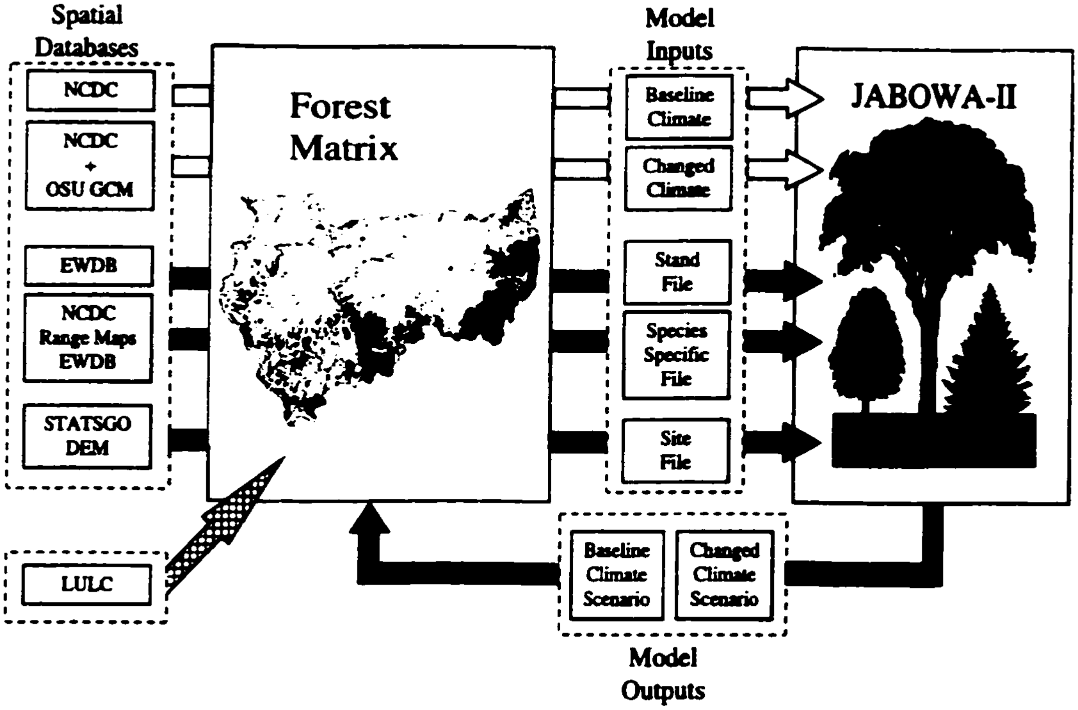

Land Use or Land Cover Type
Urban or Built-up
Agriculture
Rangeland
Forest
Water
Wetland
Barren
State Boundaries
100
0
100
200 Kilometers
Albers Projection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NCDC
NCDC + OSU GCM
EWDB
NCDC Range Maps EWDB
STATSGO DEM
LULC
Forest Matrix
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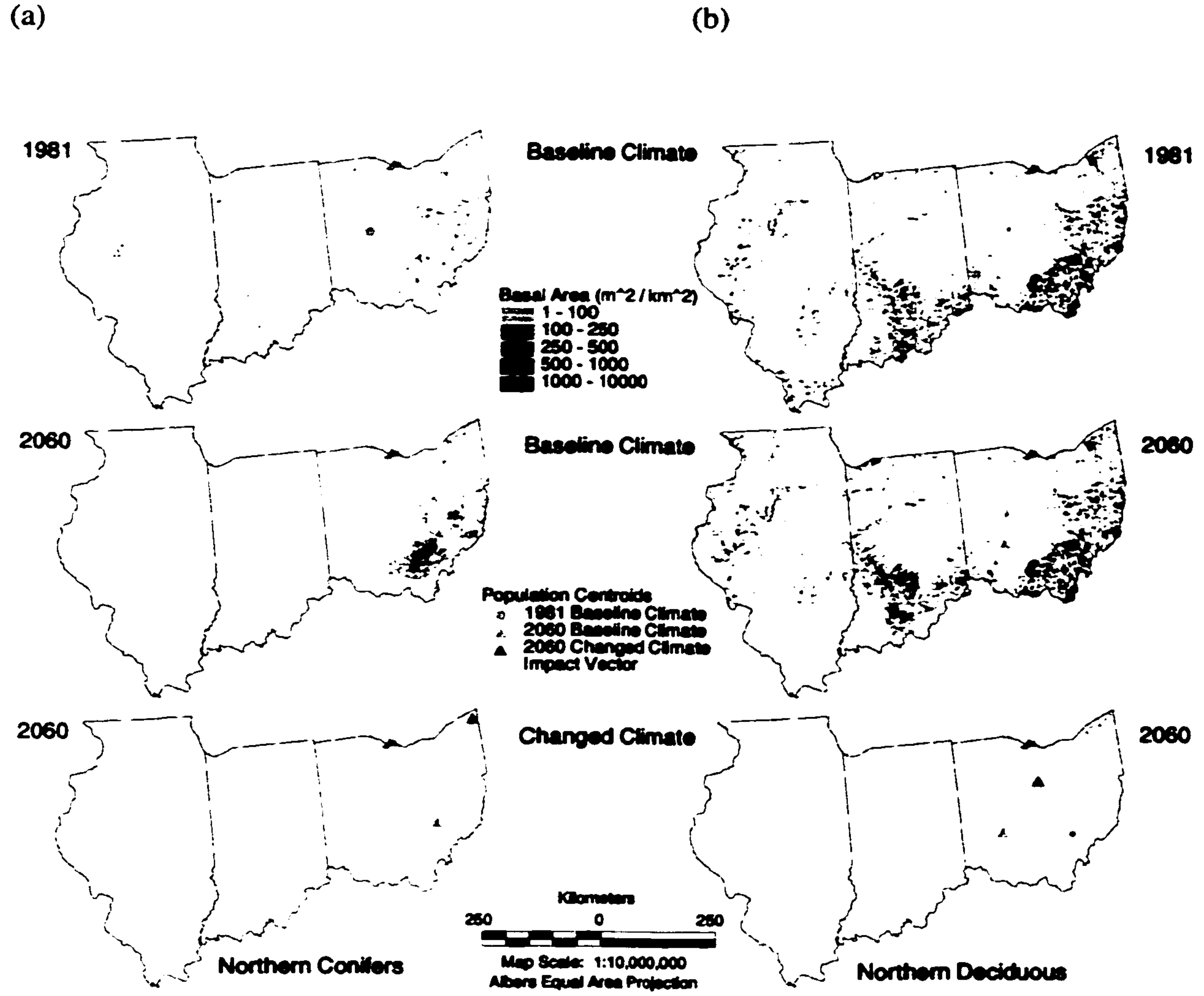
Baseline Climate
Changed Climate
Stand File
Species Specific File
Site File
JABOWA-II
Baseline Climate Scenario
Changed Climate Scenario
Model Outputs

(a)
(b)
1981
Baseline Climate
1981
2060
Baseline Climate
2060
2060
Changed Climate
2060
Basal Area (m^2 / km^2)
1 - 100
100 - 250
250 - 500
500 - 1000
1000 - 10000
Population Centroids
1981 Baseline Climate
2060 Baseline Climate
2060 Changed Climate
Impact Vector
Kilometers
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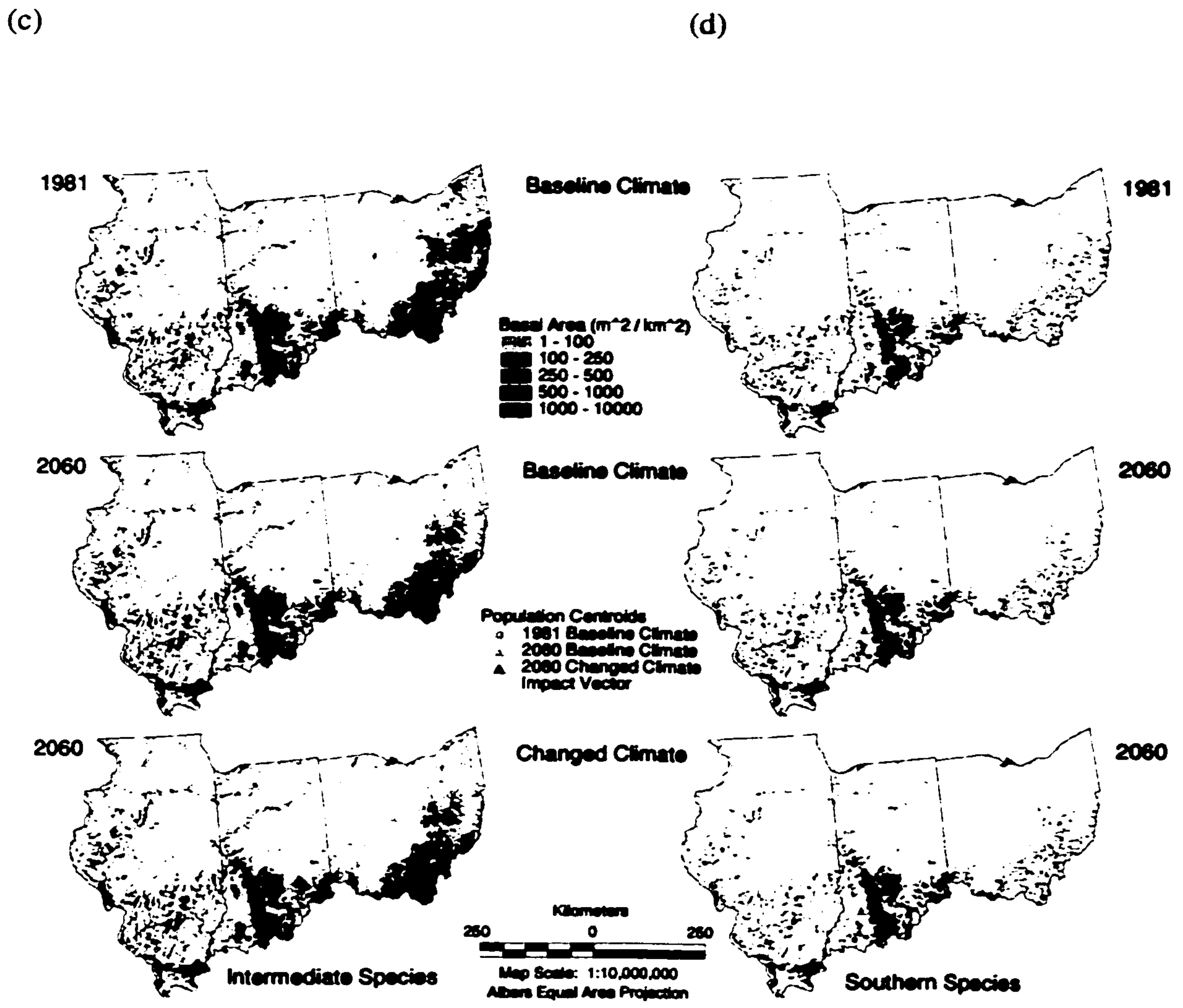
Albers Equal Area Projection
Northern Conifers
Northern Deciduous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Baseline Climate
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Baseline Climate
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Population Centroids
1981 Baseline Climate
2060 Baseline Climate
2060 Changed Climate
Impact Vector
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Changed Climate
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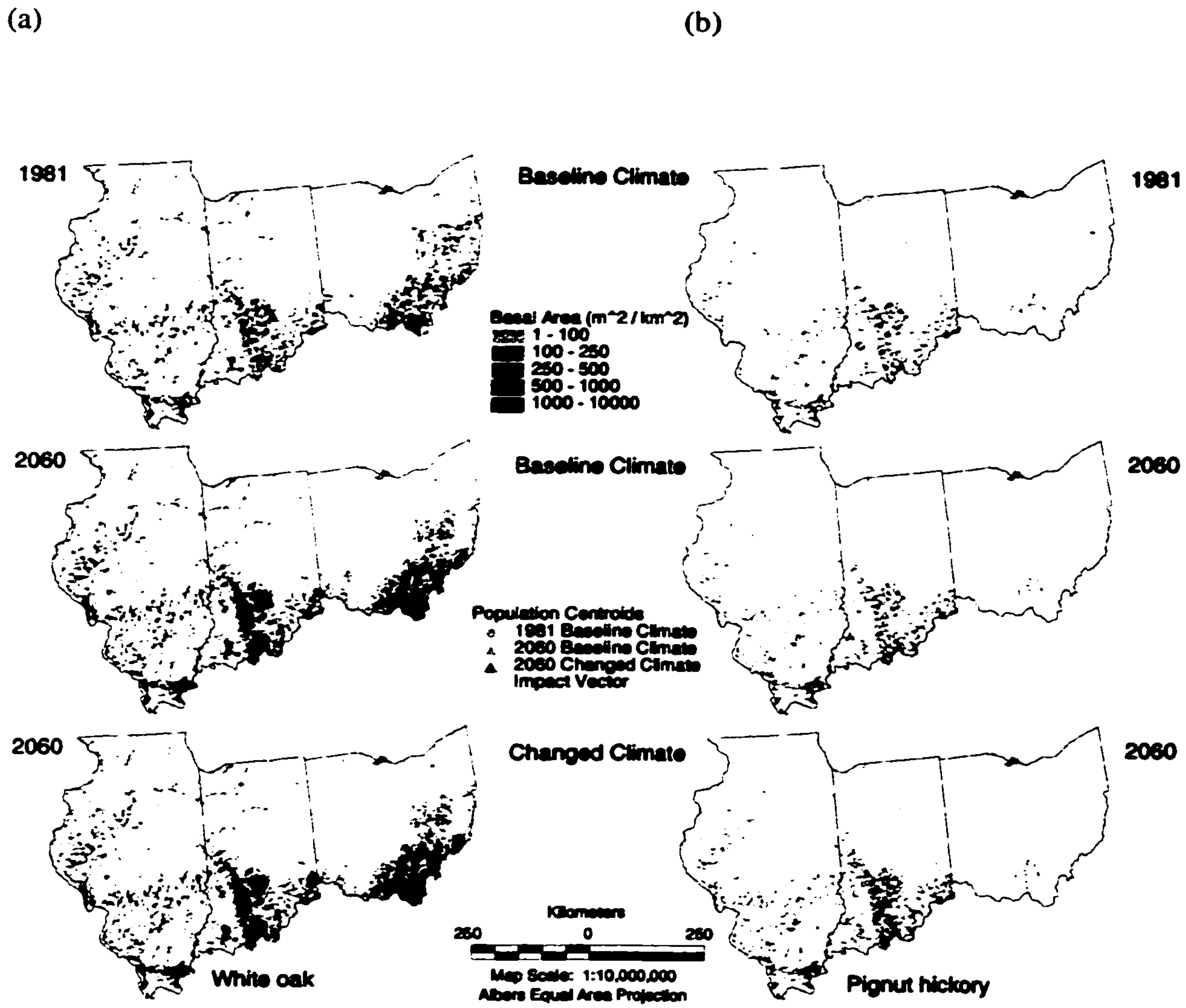
Albers Equal Area Projection
Intermediate Species
Southern Species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2060 Changed Climate
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Albers Equal Area Projection
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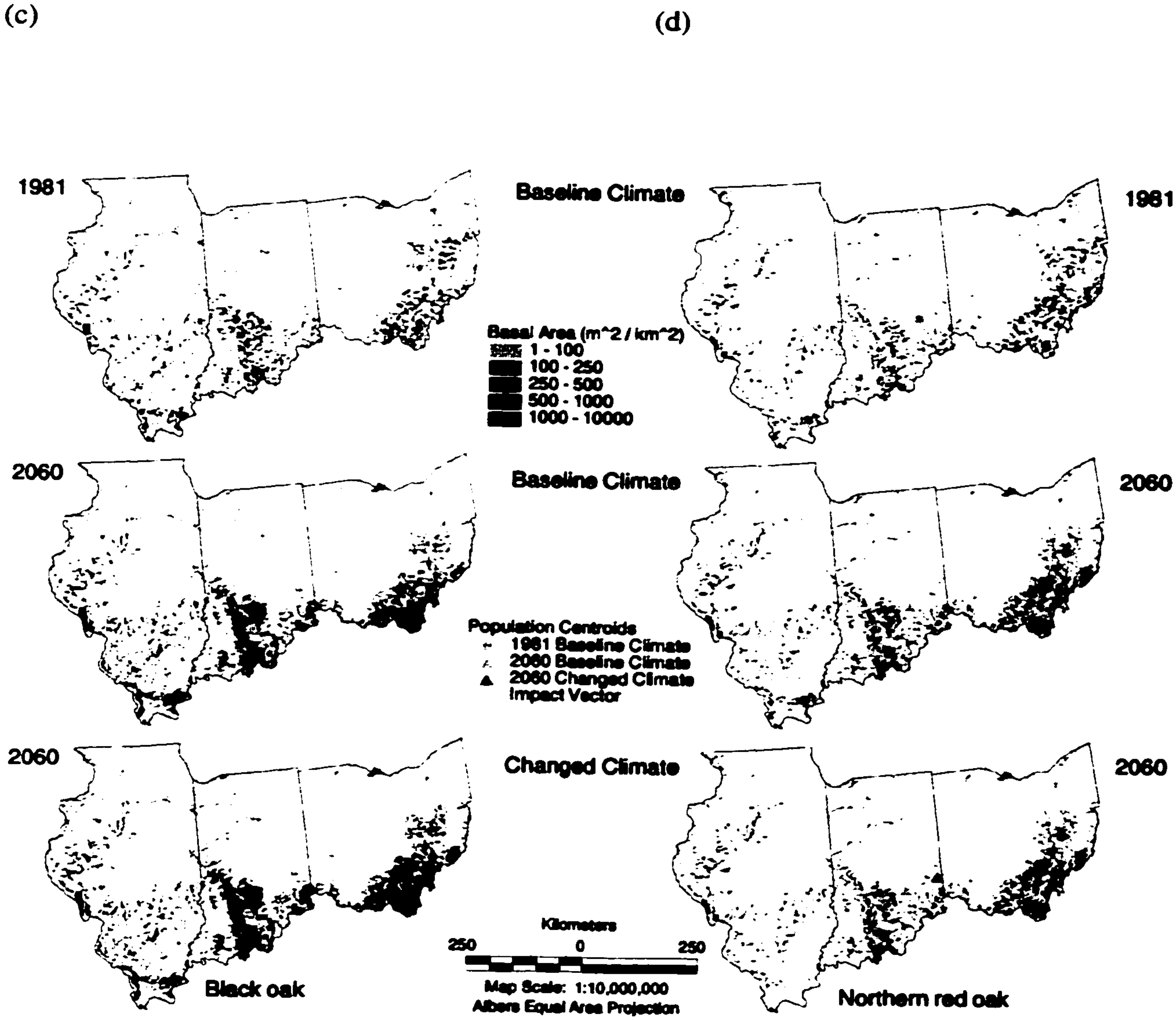
Pignut hickory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2060 Changed Climate
Impact Vector
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Kilometers
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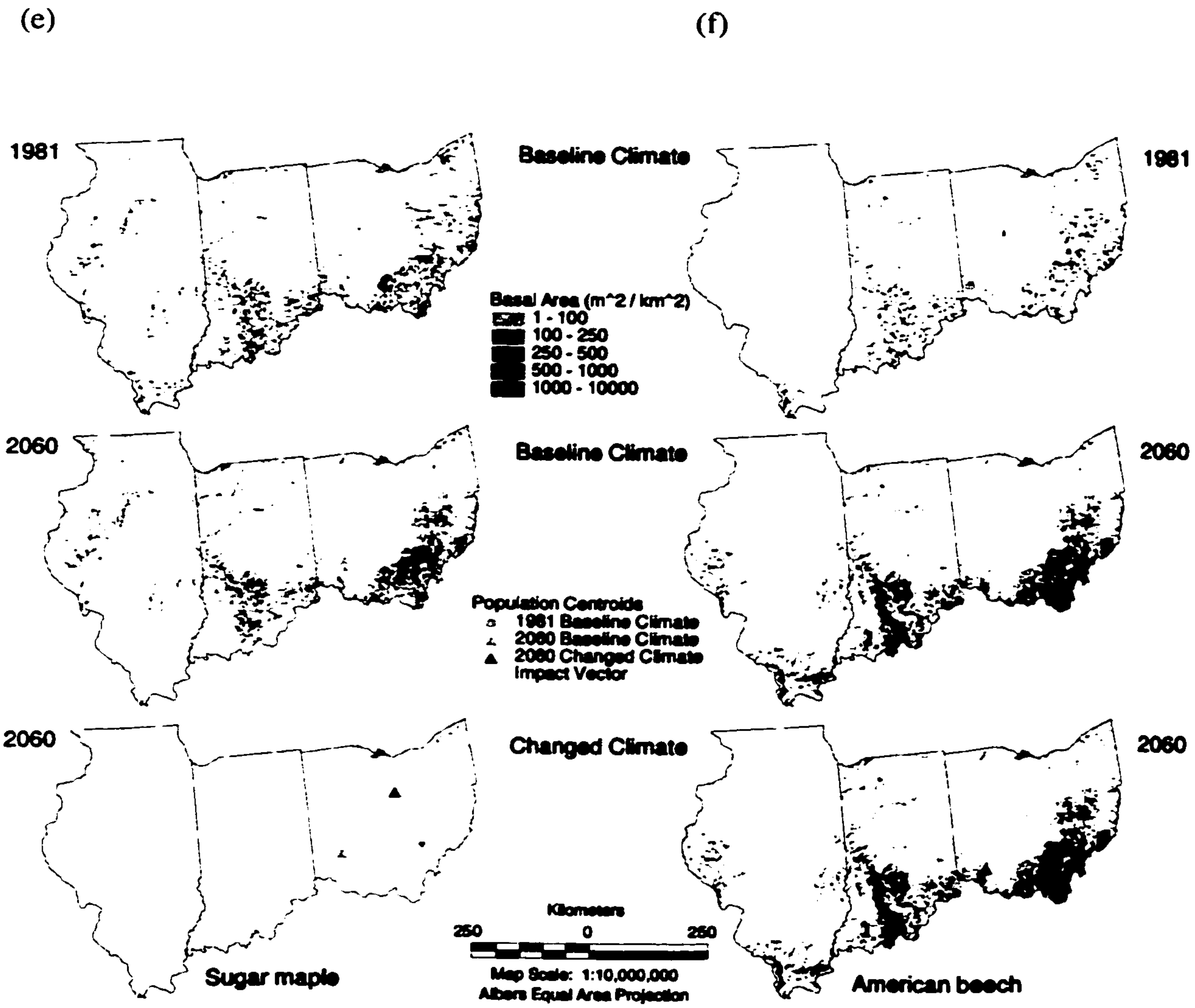
Map Scale: 1:10,000,000
Albers Equal Area Projection
Black oak
Northern red oak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Population Centroids
1981 Baseline Climate
2060 Baseline Climate
2060 Changed Climate
Impact Vector
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Changed Climate
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Kilometers
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Map Scale: 1:10,000,000
Albers Equal Area Projection
Sugar maple
American beech

Chapter 5:

Forest cover change in western Honduras: the role of socio-economic and biophysical factors, local institutions, and land tenure

Submitted to: *Mountain Research and Development*

Jane Southworth and Catherine Tucker

Abstract

Tropical deforestation poses a threat to ecological sustainability and socioeconomic development in many parts of the world. Information on forest transformations is especially pertinent in sensitive ecological zones, such as mountainous regions, where forest cover protects steep slopes and thin soils from erosion. Such areas are frequently unsuitable for agriculture, but inhabitants may have few alternatives to meet subsistence needs. Understanding the relationship between human behavior and forest change poses a major challenge for development projects, policy-makers, and environmental organizations that aim to improve forest management. Knowledge of the areal extent of forest cover and the processes of change represent an integral step, but in many areas of the globe these are still relatively unknown.

This research addresses forest cover change in a community in the mountains of western Honduras. Between 1987 and 1996, 9.77 km^2 of land was reforested and only 7.48 km^2 was deforested, as determined by satellite image analysis. This reversal in the dominant trend of deforestation in Latin American countries, including Honduras, relates to socioeconomic, biophysical, and technological processes. Forests remain primarily on steeper slopes, at higher elevations, and at a distance from settlements and roads. A county ban on logging has allowed regrowth of previously logged areas. Agricultural intensification appears related to abandonment of some marginal lands. Processes of privatization have been occurring; private forests reveal higher reforestation and lower deforestation rates than communal forests. Privatization has favored the wealthy. Thus, the majority has had to depend on shrinking communal forests.

Keywords: reforestation, remote sensing, privatization, GIS, land tenure.

Introduction

The mapping of tropical forest biomes has received global attention due to the rapid rates of change that have been reported (Mayaux and Lambin 1995), and the significance of such changes to the world's climate system, biological diversity, and the global carbon cycle (Apan and Peterson 1998). The most frequently used technique for the mapping of tropical forests or change rates is by the visual and digital analysis of satellite data (Hall *et al.* 1991). On-the-ground field studies prove too costly to use as a sole approach to such analysis. Remote sensing from satellites allows the production of maps at a greater spatial extent and over frequent time steps, while saving time needed in the field for map testing and correction, interviews, and vegetation analysis.

Several studies have used remote sensing to map patterns of deforestation and to analyze the rates of such changes in the tropics and elsewhere (Hall *et al.* 1991, Roughgarden *et al.* 1991, DeFries *et al.* 1997, Woods and Skole 1998). Such studies have proven useful for interpreting the causes of deforestation and the impact of such changes on the region. Monitoring of change (be it deforestation or reforestation) is frequently perceived as one of the most important contributions of remote sensing technology to the study of global ecological and environmental change (Roughgarden *et al.* 1991, Apan and Peterson 1998). This study incorporates remote sensing for mapping change, but also integrates socioeconomic, land use, and biophysical data to interpret the forest change trends revealed by image analysis.

The study focuses on a major section of the county of La Campa in the mountains of western Honduras, which offers an important opportunity for forest cover analysis due to the high amount of forest remaining, approximately 60 %. La Campa has traditionally left forests under communal management, but pressures for privatization have led to the creation of private forests on the more accessible portions of communal lands. At the local and national levels, agricultural intensification relates to technological change due to modernization, as well as population pressure. The study also encompasses a surrounding area of the Department of Lempira for a broader perspective on the processes observed in La Campa. Most studies of Honduran forests focus on the high biodiversity areas of the northern coast, or the central and eastern pine forests. The mountainous zones of western Honduras also merit analysis due to their naturally occurring forests, the potential for forest regrowth and production, and socioeconomic processes of change.

Methodology

Study Area

The study site in La Campa contains rugged topography, generally shallow soils, and vegetation dominated by pine-oak forests (Figures 1 and 2). Most forests occur on relatively inaccessible, steeply sloping terrain (Figure 1). Subsistence production of maize and beans represents the most common agricultural land use. The higher elevations are becoming increasingly important for coffee production, which is now one of Honduras' leading exports (Tucker 1999; Instituto Hondureño del Café 1998). Typical of the region, timber represents the most important natural resource. Pine trees (*Pinus oocarpa, Pinus patula spp. tecunumani*, and *Pinus pseudostrobus* above 1800 m) thrive on the acidic soils (Styles and McCarter 1988). Oak (*Quercus spp.*) grows where soils are deeper (Pineda Portillo 1984). Regional sawmills extracted lumber from La Campa starting in the 1960s until the county banned logging in 1987. Agriculture and logging have substantially deforested the accessible areas of the county, as in the rest of western Honduras.

The climate of the area is temperate, with a wet season and a dry season. The rains usually begin between late April and early June, and continue into September or October. La Campa receives an average of 1293 mm of rainfall per year (Tucker 1996), but annual precipitation varies greatly. By contrast, the surrounding Lempira area (Figure 2), which is included in the change analysis, encompasses Celaque National Park with cloud forest averaging over 2000 mm of rainfall annually (Zúniga Andrade 1990).

Socio-economic and interview data

The current work in La Campa is built upon an in-depth understanding of the land use and changes gained through extensive survey and interview research conducted in 1993-1994 and in the summer of 1995. The fieldwork involved socioeconomic and demographic surveys in 113 households. In addition, researchers conducted formal and informal interviews exploring forest uses and land cover changes with heads of household, local authorities, regional foresters, and representatives of national and nongovernmental institutions active in La Campa and surrounding counties.

Forest plot and training sample data

Fieldwork to ground truth the 1996 Thematic Mapper (TM) satellite image and collect forest data occurred in 1997 and 1998. In La Campa, 79 forest plots were sampled to collect data on vegetation, soils, and topography. These data included tree height, diameter at breast height (dbh), canopy cover, ground cover, slope, aspect, and altitude, among other observations. Forest plots were selected randomly in representative communal and private forests, to allow for comparison of forest based on land tenure. Researchers collected 131 training samples throughout the Lempira area to represent various land cover classes (e.g., urban, water, bare ground, young fallows, pasture, annual agriculture, perennial agriculture and forest). Training samples are observations of specific land covers, selected based on satellite image analysis. These observations are less detailed than forest plots, but broadly describe larger areas with homogeneous land cover.

Satellite image analysis

Landsat TM images were obtained for March 1987 and March 1996. Geometric rectification was carried out using 1:50,000 scale maps and the nearest neighbor resampling algorithm, with a root mean square (RMS) error of less than 0.5 pixels (< 15 m). Using the same basic procedure, the rectified 1996 image served to rectify the 1987 image. An overlay function verified that the two images overlapped exactly across the two image dates.

Following rectification, calibration procedures corrected for sensor drift and other differences, such as variations in the solar angle and atmospheric conditions. Without such calibration, change detection analysis may evaluate differences at the sensor level rather than changes at the Earth's surface. The images underwent radiometric calibration, atmospheric correction, and radiometric rectification.

The training sample data were used to determine the land cover classes on the ground and then train the satellite image to recognize them. Classes for agriculture, young fallows (approximately 1-3 years), cleared areas, bare soil, water, and urban areas were aggregated to create a non-forest class. Land cover maps of forest and non-forest cover for 1987 and 1996 were derived by independent supervised classification of the two Landsat images, using a Gaussian maximum likelihood classifier. Only two cover classes were used to simplify the change analysis and to minimize the ground-truthing needed to develop the classification (Spies *et al.* 1994).

With classification accuracies exceeding 80%, classified images generally agree visually with actual land cover. Our classification accuracies (85.7% for 1987 and 87.9% for 1996) indicate high validity. Following classification, change detection analysis can be undertaken. Change detection is a technique used to determine the change between two or more time periods of a particular region or for a particular land cover, by providing quantitative information on spatial and temporal distribution. It offers an important tool for monitoring and managing natural resources (Macleod and Congalton 1998).

Four aspects of change detection are important when monitoring naturally-occurring or human-induced phenomena: (1) detecting the changes that have occurred, (2) identifying the nature of the change, (3) measuring the areal extent of the change, and (4) assessing the spatial pattern of the change (Macleod and Congalton 1998). Estimation of change requires the acquisition of images for the same area over two or more time periods. The images are classified into land cover classes (here forest and non-forest), and then overlaid using ARC/INFO™ software in order to calculate the rates and types of changes across each image. TM data allows comprehensive coverage of large areas and identification of coarse but key classes of vegetation for global studies (Schimel 1995).

Changes in land cover between 1987 and 1996 were detected using an image grid addition technique across both images that resulted in four possible classes (i.e., forest in both images, reforestation from 1987 to 1996, deforestation from 1987 to 1996, and non-forest in both images). This post-classification grid analysis led to a newly classified image incorporating information from both images (Mertens and Lambin 1997), producing a categorical map (change image). This image is associated with a change matrix, which gives the area for each class and its changes over the time period.

GIS: Accessibility surface

The analysis of change classes addressed the influence of distance from the nearest road and the nearest settlement for the Lempira area, including La Campa. This was done by using ARC/INFO™ to create buffers at 1 km intervals up to a 5 km distance from roads and settlements. These buffers were then related to the change class image. A second analysis then incorporated this distance information along with elevation and slope, which was obtained from a digital elevation model, to measure the importance of topography in this region. This step created an accessibility surface (with a scale of 2-29, with 29 being most inaccessible) based on distance, slope, and elevation. Subsequently, mean accessibility classes were calculated for each forest cover change class.

Land Tenure

The eight forests sampled in La Campa included four communal forests and four private forests. Researchers also interviewed each of the owners of the private forests, and multiple users of the communal forests, to learn of their uses, management practices, and level of exploitation. The analysis of communal and private forest conditions incorporated data from the forest plots and the change image.

Results

Socioeconomic and interview data

La Campa households depend heavily on firewood from communal forests for cooking; some private forest owners used firewood from communal forests to reduce exploitation of their own land. Households also use forests to graze livestock, harvest timber for construction and fences, and collect mushrooms and medicinal plants.

Interviews and survey responses, as well as the change analyses, indicate that processes of agricultural intensification are occurring in La Campa. Population growth has been associated with these transformations; from 1961 to 1988 (the most recent census), La Campa's population nearly doubled (Tucker 1996). Intensification has included a shift from slash-and-burn agriculture to extended cultivation with short fallows, adoption of chemical fertilizers and soil conservation techniques, and expanded use of animal-drawn plows. According to interviews, the adoption of fertilizer began in the 1960s, and soil conservation in the 1980s. Of the 38 farmers interviewed in 1994 about their agricultural practices, 95% used chemical fertilizers on their crops. Elders reported that during their youth (~40-50 years ago), they cleared new fields annually from forest or old fallows, and abandoned them after one to three years. Out of the 108 households surveyed in 1994, 71% noted that they did not clear any new fields that year, but planted only their existing fields. Cultivated fields had been planted for an average of eight consecutive years, and preceding fallow periods averaged 12 years.

Satellite image change analysis

From the Landsat TM satellite image analysis, forest cover change across the study area between 1987 and 1996 shows an overall trend of reforestation. Within the 80.09 km^2 area, 9.77 km^2 was reforested, 7.48 km^2 was deforested, 23.72 km^2 remained cleared, and 39.12 km^2 remained forested (Table 1). Determining these rates of change as a percentage cover change based on the initial area available, we see that 16.06% of available forested land in 1987 was deforested by 1996, and 29.17% of available cleared land in 1987 was reforested by 1996 (Table 1). Hence, in this study area, reforestation is the overall trend in forest cover change during this time period.

Within the larger Lempira study area of 908.84 km^2, 91.78 km^2 was reforested between 1987 and 1996, and 87.19 km^2 was deforested. The area remaining forested across both dates was 403.57 km^2, and the area remaining cleared across both dates was 326.3 km^2 (Table 1). Of the forested area in 1987, 17.77% was deforested by 1996 and of the area cleared in 1987, 21.95% was reforested by 1996. These results are not as significant as those at the smaller scale of La Campa, but they still represent a reforestation trend over this larger region.

Accessibility analysis

Results from the distance analysis for the Lempira area show that most clearing occurs within 5 km of major settlements; beyond this, forest cover dominates. Most reforestation and regrowth occurs at distances greater than 1 km from roads and settlements. Within 1 km, agricultural fields dominate. The inclusion of slope and elevation within this analysis, by creation of the accessibility surface, provided greater explanatory power for the spatial distribution of forest cover change (Table 2). Forested areas remain in the most inaccessible regions, on the steeper slopes and higher elevations that tend to be far from roads and towns. Clearings usually occur on gentler slopes and lower elevations, closer to roads and towns (Table 2, Figure 3), although increasingly deforestation is occurring in more highly inaccessible areas, for coffee production. This trend will only increase in the future as the limited areas of current coffee production expand.

Land tenure

The biophysical conditions of the forest cover, and processes of the forest cover change, relate to land tenure (Figure 4). The private forests cover a smaller area, but on average they present greater tree species diversity, larger tree dbh (diameter at breast height, or 137 cm), and greater tree height (Table 3). Communal forest areas involve larger areas, and on average present smaller dbh and shorter trees (Table 3). The 1997 forest fieldwork, designed to collect comparable data in private and communal forests, did not find these differences to be statistically significant (Tucker 1999). The subsequent fieldwork in 1998, and the completion of the change analysis, provided additional data to show that private forests have had lower rates of deforestation and higher rates of reforestation compared to the communal forests (Figure 4).

Discussion

The various data sources point to interrelated factors in La Campa's forest cover trends. Reforestation relates to regeneration of logged areas, privatization of some previously communal lands, and abandonment of marginal agricultural lands. Deforestation, while less than reforestation, includes clearing of fallows for agricultural fields and clearing for new coffee plantations - often in areas of steeper slopes and more mature forests. Accessibility shapes the location and extent of these transformations.

The transition of agriculture from a slash-and-burn system to more intensive cultivation appears to involve abandonment of some fields on slopes too steep for plowing. Intensively cultivated fields produce larger harvests in smaller areas than the slash-and-burn fields, thus farmers require less land to meet their subsistence needs (Netting 1993). The conditions in La Campa fit the scenario predicted by Boserup (1967) as conducive for agricultural intensification. Under conditions of population growth and limited options to acquire new agricultural land, intensification and technological change become desirable, once existing techniques do not meet demands for increased production. If population density continues to increase, we expect that successively more marginal lands will be brought under production. Thus, abandonment of marginal agricultural fields is likely to be a temporary situation.

Steep slopes, and increasing distances from roads and settlements, represent constraints on accessibility for human use. Creation of private forests usually occurs close to roads; this accessibility facilitates monitoring. This phenomenon of increasing privatization of land does account in part for areas of reforestation being in more accessible regions than the deforested areas (Table 2). Communal forests remain on less accessible land, parts of which were logged in the 1970s and 1980s. Interviews and observations indicate that regeneration followed logging on steeper lands further from roads, while logged areas near roads or on more level land generally experienced conversion to agriculture. Communal forest conditions reflect not only residents' uses, but also historic intervention by outsiders.

Thus, reforestation has taken place where people once logged or cleared forests for agriculture, and they may do so again as economic and social conditions evolve. Current reforestation processes also link to changing human preferences and local institutional decisions. In recent decades, families have preferred to settle in villages to facilitate children's school attendance rather than establishing isolated homesteads. This has concentrated the pressure on the communal forests nearest settlements (Figure 4). Moreover, the countywide prohibition on logging has prevented new clear-cuts, and allowed natural regeneration, since its imposition in 1987. People strongly support the logging ban; they perceive it as a necessary measure to protect forests from exploitation by outsiders, and preserve forest resources for their subsistence uses, although some forest transformations for agriculture have been allowed. Even private forest owners have complied with the ban.

While accessibility influences processes of forest change, a variety of factors shape people's choices. Economic incentives and road improvements can overcome topographic and transportation constraints. With national programs and development funds, La Campa has prioritized road construction and increased market-oriented production, such as coffee. Interviews and observations of coffee plantings with farmers revealed incursions to relatively inaccessible zones of the highland forests (Table 2), in anticipation of new roads. Although the total area in coffee by 1996 represented less than 2% of county land, the ongoing process promises to make a great impact on the landscape. The communal and private forests sampled in this study lie at lower elevations less suitable for coffee, and they have been less subject to road expansion.

The patterns found in the La Campa study site appear as well in the surrounding Lempira region, where the Cordillera de Celaque (Honduras' highest mountain peaks) continue to be covered in old growth cloud forest. The national perspective, however, provides a more typical scenario, in which economic and demographic pressures, associated with inequitable distribution of land and resources, results principally in deforestation. The reforestation trend discovered within this study's limited time span may represent a transitional stage. Wealthier households have claimed more land for private use than poorer households. Land privatization has decreased the area available for use by the majority, creating a situation in which ever more people depend upon fewer communal resources. The processes of population growth, increasing socioeconomic inequality, and market-oriented agricultural production seem likely to lead to a dominant deforestation trend in the future.

Conclusions

The main conclusions from this research are:

- Reforestation is the dominant trend in forest cover change across the study area of La Campa.
- Agricultural intensification has led to increased reforestation rates due to the abandonment of less profitable fields.
- Spatial patterns of change relate to accessibility and land tenure, with forests remaining in predominantly inaccessible regions and communal forests having greater deforestation trends than private forests.

- Future increases in deforestation are likely due to increasing population density, socioeconomic inequality, and market-oriented agriculture, resulting in an increasing pressure on forest resources.

La Campa's local institutions have contributed to an increase in forest cover, in conjunction with processes of forest regrowth linked to privatization, abandonment of some marginal fields, and biophysical conditions that tend to limit human use of inaccessible areas. The implications of this research are particularly relevant for policy design and implementation, as policy-makers tend to reach decisions based upon aggregate, macro-level data. Such data can obscure areas such as La Campa, where reforestation trends contradict the expectation. For La Campa, national policies designed to slow deforestation could promote it, if they compel changes in local institutions that restrict forest exploitation (e.g., logging). The greater threat to forests, however, appears to be economic development incentives that encourage deforestation.

Ongoing research will incorporate fieldwork data from spring 2000, and image analysis of a 2000 Landsat TM scene. This time-step will reveal whether reforestation trends continue to exceed deforestation in the county. In addition, the differences between private and communal forests will probably become more pronounced as communal areas remain subject to increasing exploitation.

Acknowledgments

This research was supported by the National Science Foundation (NSF) (SBR-9521918) as part of the ongoing research at the Center for the Study of Institutions, Population, and Environmental Change (CIPEC) at Indiana University. A NSF Dissertation Improvement Program Grant (SBR-9307681) funded the 1993-94 research. Fieldwork benefited from the invaluable research assistance of Stephen McLaughlin, Jessica Fonseca, Martha Moreno, Paul Turner, Soledad Martínez and Eduardo Bedoya. We thank Laura Carlson for help with the GIS analysis. Finally, we are grateful to Dr. J. C. Randolph, Dr. Elinor Ostrom, and Michael Kohlhaas for their comments on earlier drafts.

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Table 1: Change matrix results for forest change for the La Campa study area and the larger Lempira area, between 1987 and 1996, for forest (F) and nonforest (NF).

	La Campa	**Lempira**
NF in 1987 to F in 1996	9.77 km^2	91.78 km^2
NF in 1987 and 1996	23.72 km^2	326.30 km^2
F in 1987 and 1996	39.12 km^2	403.57 km^2
F in 1987 to NF in 1996	7.48 km^2	87.19 km^2
% of forested area deforested by 1996*	16.06 %	17.77 %
% of non-forested area reforested by 1996*	29.17 %	21.95 %
Total area of study site	80.09 km^2	908.84 km^2

* These values are calculated based on the area available for deforestation/reforestation at each location, i.e., how much of the forested land at a specific location was deforested by 1996. Hence this value is a direct function of the initial land area available in 1987 as either forest or non-forest.

Table 2: Comparison of forest change class and mean accessibility class

Forest change class	**Mean accessibility class (Scale 2-29, with 2 = most accessible)**	
	Lempira study area	**La Campa**
Forest in 1987 and 1996	11.03	6.75
Forest in 1987, non-forest in 1996 [deforested]	7.45	5.97
Non-forest in 1987, forest in 1996 [reforested]	7.25	5.66

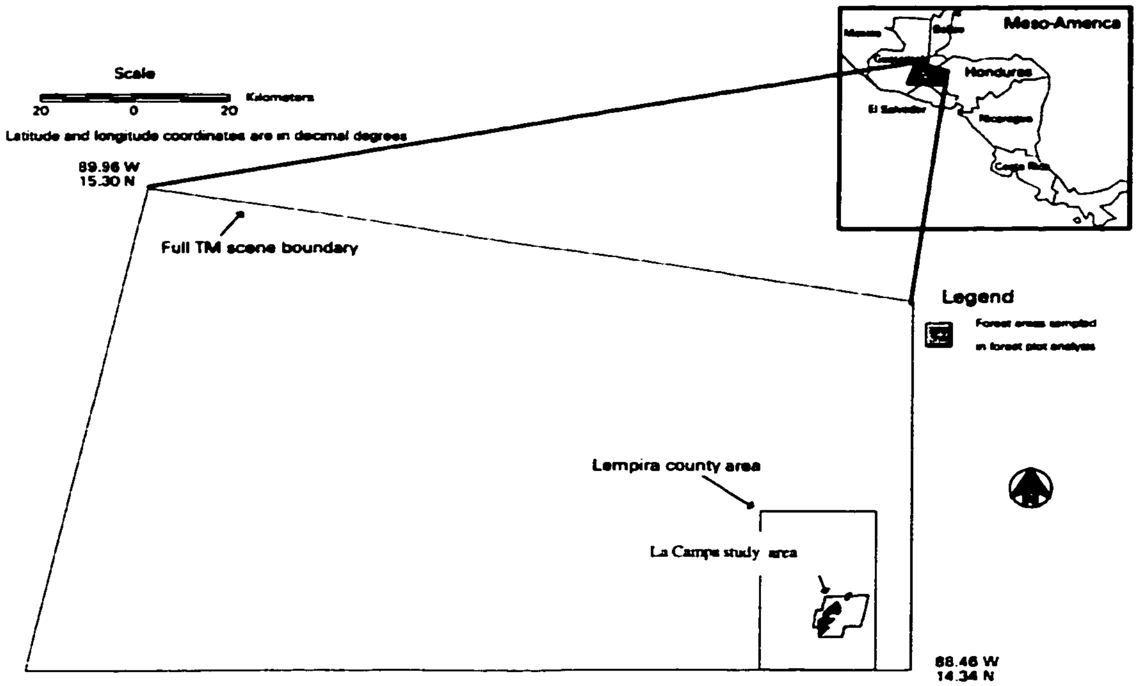
Table 3: Communal versus private forest ownership: forest plot data by tenure

	Private	**Communal**
Total Est. Area of Study Forests (ha)	25.2	812.5
Total Plots Sampled	21	58
Mean tree[1] dbh (cm)	17.7	15.6
Mean tree[1] height (m)	11.3	10.0
Tree species richness[2]	7	17
Projected tree species/ha	11.1	9.3
Projected tree stems/ha	376	472

[1] These figures exclude saplings. Trees are defined as a dbh of 10 cm or greater; dbh was taken at 137 cm above the ground.

[2] This figure includes species found as saplings (less than 10 cm dbh).

List of Figures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15.30 N
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Mexico
Belize
Guatemala
Honduras
El Salvador
Nicaragua
Costa Rica
Legend
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Lempira county area
La Campa study area
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14.34 N

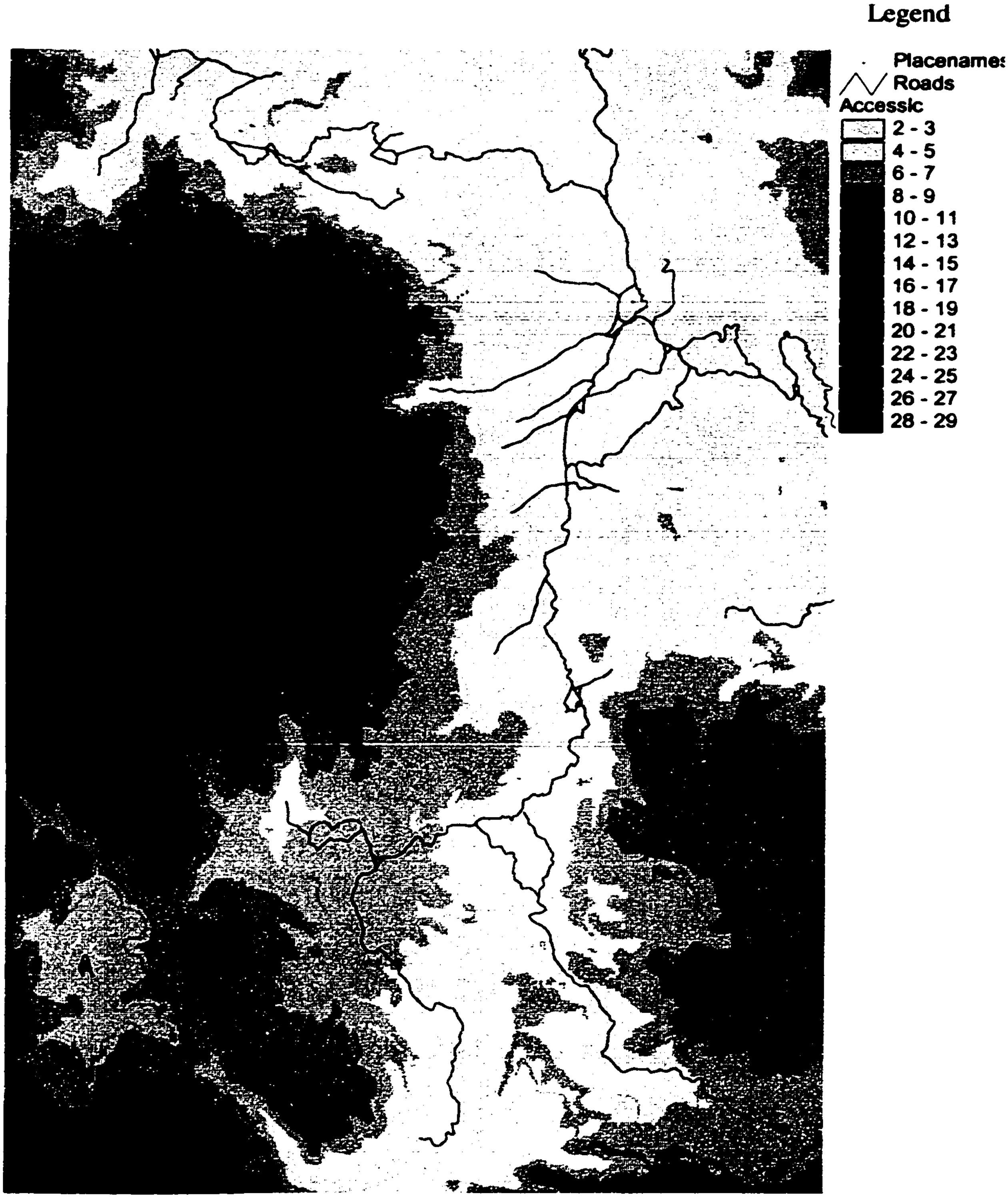
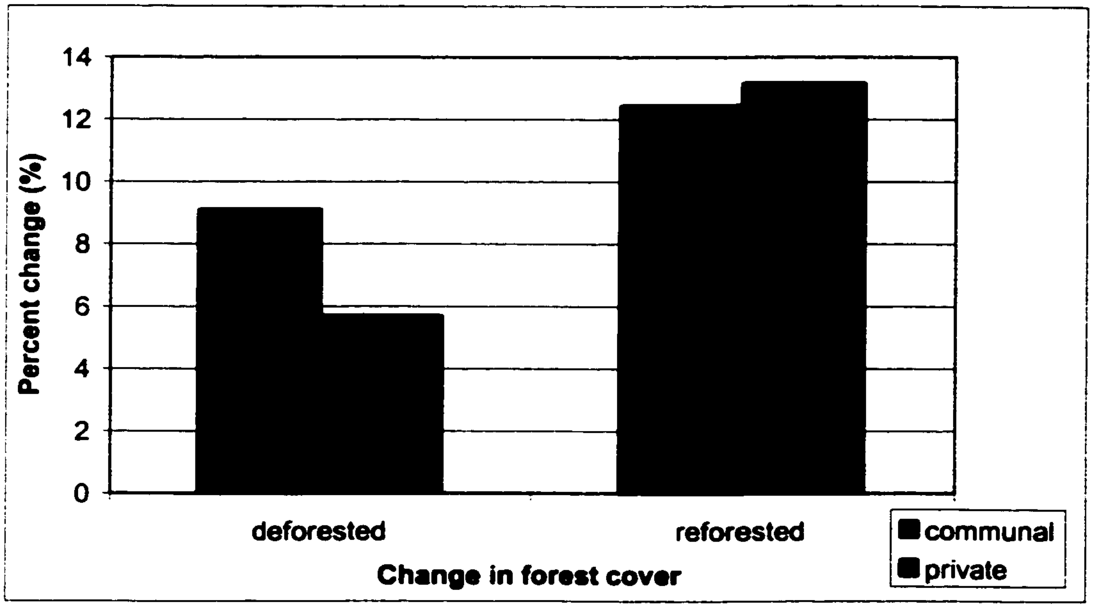


Image analysis and creation by Jane Southworth


14
12
10
8
6
4
2
0
Percent change (%)
deforested
reforested
Change in forest cover
communal
private

Chapter 6:

An Assessment of Landsat TM Band 6 Thermal Data for Analyzing Land Cover in Tropical Dry Forest Regions

Jane Southworth

Abstract

This research investigates the utility of integrating Landsat band 6 thermal data for land cover classification and, specifically, for the differentiation between successional stages of forest growth. Such successful differentiation has become critical for the assessment of land cover and land use changes after deforestation /clearing. The ability to monitor and measure changes in land cover within these areas of deforestation or clearing is critical to addressing questions concerning changing climate and other issues pertaining to deforestation in many tropical regions. The study area of this research is within the state of Yucatan, Mexico, which is a region of predominantly tropical dry forest. Tropical dry forests cover more area, and are as greatly impacted, as humid tropical forests, yet there have been few studies of their structure, functions, and processes. Given the locations of many tropical dry forest regions, these areas will be increasingly affected in the future due to global and regional socioeconomic and political pressures.

This research uses a technique of land cover classification utilizing Landsat TM thermal band data. Thermal band data measures the emission of energy from the earth's surface and as this is a function of the surface cover it can be used as a determinant of land cover type, based on the temperatures measured. This technique provides surface temperatures, which can be significant in both ecological and meteorological research.

The ability of the thermal band to differentiate between different land cover types was evaluated. Analyses included supervised classifications, vegetation indices, temperature distribution, and statistical comparisons of reflected and emitted energy patterns. Discriminant analysis revealed that band 6 contains considerable information for the discrimination of land cover classes in the dry tropical forest ecosystem, with a coefficient of 0.354. However, when used in a vegetation indices band 6 is able to increase the discrimination, with coefficients of 0.188, the third highest score recorded.

1. Introduction

Gaining a better understanding of the ways that land cover and land use practices evolve is a primary concern for the global change research community. Changes in land cover impacts climate, as well as the diversity and abundance of terrestrial ecosystems. Hence, the ability to project future states of land cover is a requirement for making predictions about other global changes, because anthropogenic causes drives land-cover change (Turner et. al., 1993).

In tropical regions, many land cover changes of ecological and climatic significance are currently taking place such as colonization of marginal lands, deforestation, drylands degradation, landscape fragmentation, and rapid urbanization (Lampin, 1994). Although tropical dry forests cover more area than humid forests, there have been few studies of their functions, structure, and processes even though they are greatly affected by human activity (Whigham et. al., 1990). Such analyses require repetitive surveys and in this context remote sensing can be a powerful tool (Estève et al., 1998). In addition, these issues need to be monitored and studied across a range of temporal scales and across local, regional, and global spatial scales (Hall et al., 1991). Again, this highlights the usefulness of remote sensing for addressing such research areas.

Spatial information on existing land uses is important for the analysis of current environmental conditions and to estimate and determine future land use activities. Traditionally, land cover has been used as the principal surrogate for land use when remotely sensed data have been used. Although land use and land cover may be closely related, they are conceptually different, describe two different themes, and are determined by two different, non-interchangeable data sets. Thus, accurate analysis of land cover characteristics using remotely sensed data is a prerequisite for determining land use, which is a necessary input for Land Use Land Cover Change (LULCC) models. The use of Landsat 5 Thematic Mapper (TM) data for land cover classification of vegetation types is becoming increasingly successful (Li *et. al.*, 1994; Mausel *et. al.*, 1993). The ability to monitor and measure changes in land use and land cover within these areas is critical to addressing questions concerning changing climate and other issues pertaining to deforestation in many tropical regions (Li et al., 1994). In addition we can measure land-surface temperature, which is one of the most important land-surface parameters (Wittich, 1997; Sobrino et al., 1991).

The objective of this research is to integrate thermal band imagery analysis into vegetation land cover analysis methodologies. The Landsat TM thermal band, usually designated as TM band 6, is sensitive in the region 10.4-12.5 μm. It has lower radiometric sensitivity, and coarser spatial resolution (about 120 m), relative to other TM bands. Most studies on land cover and land use change using satellite data have not used Landsat 5 TM band 6 thermal data. Thermal data spatial resolution of 120 m x 120 m is advantageous when wishing to undertake a more broad scale classification scheme as is proposed here. The Landsat TM band 6 responds to varying temperatures and emissivities on the ground, producing images that show the relative differences in emitted thermal energy that correlate in part with the effects of solar heating on surfaces of varying composition and orientation. Landsat TM thermal imagery (despite its lower spatial resolution) both supplements reflected radiation images and stands alone as an information source (Short, 1996). Landsat 7, which is now in orbit, has a band 6 resolution of 60 m x 60 m, which is a tremendous improvement in resolution. This provides even greater reasons for researchers to utilize this information and incorporate surface temperature analyses into land cover classifications. In order to undertake time-series analysis utilizing band 6 thermal information one must use Landsat 5 TM Band 6 data because Landsat 7 only provides data for current time periods. This research highlights the immense usefulness and the amount of data available through this one band of information.

One of the major advantages of using Band 6 data is that this information, when converted into temperatures, can be used to link directly to other processes, (e.g., micrometeorological). Land surface processes are of paramount importance for the re-distribution of energy and moisture between the land and the atmosphere. Surface temperature is an important parameter in the characterization of energy exchange between the ground surface and the atmosphere. Landsat TM Thermal band data can be used for this purpose (Hurtado et al., 1996). These exchanges of radiative, moisture and heat fluxes affect biosphere development and the physical living conditions at the Earth's surface (Bastiaanssen et al., 1998; Hall et al., 1991). Spatial variations in land use, land cover, soils, and moisture require that spatial variability of associated meteorological conditions cannot always be obtained from a limited number of climate stations. In such instances, remote sensing data provide an excellent means of obtaining consistent and frequent observations of spectral reflectance and emittance of radiation of the land surface on a micro to macro scale. As such, remote sensing provides an instantaneous snapshot of the radiative properties of the particular land surface (Bastiaanssen et al., 1998).

The thermal band, like vegetation indices, allows for continuous representation of land cover, rather than the creation of discrete land cover classes such as in classification techniques (Lambin, 1999). Land cover changes can occur in two forms: conversion of land cover from one category to a completely different category (via agriculture, urbanization, *etc.*), or modification of the condition of the land cover type within the same category (thinning of trees, selective cutting, *etc.*) (Meyer and Turner 1992). The monitoring of land conversion from one category to another is well documented and more easily undertaken than the monitoring of change within a category. However, the thermal band allows the monitoring of "within-class" differences in a vegetated area, as even when a new land cover class is not created, differences across a surface will be evident from the temperature values (Lambin, 1999). This is important, for example, when trying to determine differences in forest type, age, or structure.

Changes in vegetation cover caused by human influence are taking place continuously, both at the micro-level (via new agricultural species and techniques), and the macro-scale (via large scale deforestation, irrigation schemes, urbanization and land cover change). In addition, areas in secondary succession following abandonment are especially important for analysis of land cover change as tropical forest regrowth areas usually have increased rates of photosynthesis, evapotranspiration, respiration, a lower albedo, and greater biotic stocks of carbon than the land they replace. Thus, the fact that large areas of deforested tropical lands support secondary succession forests is of potential significance to the global Earth-atmosphere energy and carbon budgets (Steininger, 1996). One useful tool for such analyses, in addition to recording information on the soils, vegetation, climate etc., is the use of thermal band surface temperature maps. This allows the researcher to record the changes in surface features and their resultant temperature changes (Mauser and Schädlich, 1998). In such instances, the use of a thermal band analysis is critical because it allows analysis over a greater geographical area for a given time period i.e., it is a continuous climatic data source where as most climate data is point data and is usually not well distributed spatially (especially in less developed countries).

The dark, dense, frequently moist vegetation gives forests a lower visible (385-760 nm) surface albedo than most natural or anthropogenic regions (though not to the same extent as tropical moist forests for which this effect is even greater). In addition to low visible albedo, tropical forests also exhibit low infrared emissivity. That is, while most of the incident shortwave radiation is absorbed, the emission of longwave or thermal energy is inhibited, thereby yielding a positive net radiation balance. This energy is utilized in photosynthesis and in evapotranspiration of water. The turbulence caused by the stand itself accelerates the exchange of sensible heat so efficiently, that in spite of the positive radiation balance, forest canopies are cool compared with cropland or open areas (Henderson-Sellers and Gornitz, 1984). Studies have produced evidence that for some ecosystems the present dynamic equilibrium of the atmosphere depends on the underlying vegetation, and the present climate is the consequence of the interaction between the biosphere and the atmosphere (Salati and Nobre, 1991). The canopy is both a unique subsystem of the forest and the site of fundamental interactions between vegetation and the physical environment (Parker, 1995).

The study area is located within the state of Yucatan, Mexico, and the image analyzed was collected March 27th, 1995. This region is dominated by tropical dry forest vegetation, porous soils, exponential population growth, and high rates of deforestation. The primary objective of this research is to increase our understanding and ability to utilize thermal band data in land cover studies. More specifically, this research will:

1. Assess the effectiveness of thermal band information for vegetation studies of successional change;
2. Evaluate the additional information provided by the thermal band for vegetation studies;
3. Incorporate the use of band 6 information into studies which currently use only data from the reflective bands; and
4. Determine the most effective techniques (both statistical and image-based) for use in remote sensing of land cover change.

Background on Thermal Radiation

Variations in emitted energy in the far infrared provide information concerning surface temperature and thermal properties of soils, rocks, vegetation, and man-made structures. The detection of specific properties leads to inferences of the identities of surface materials. All objects at temperature above absolute zero emit thermal radiation, although the intensity and peak wavelength of such radiation varies with the temperature of the object. For remote sensing in the visible and near infrared contrasts in the abilities of objects to reflect direct solar radiation to the sensor are examined. For remote sensing in the mid and far infrared spectrum, differences in the abilities of objects and landscape features to absorb shortwave visible and near infrared radiation, and then to emit this energy as longer wavelengths in the mid and far infrared regions, are examined.

Remote sensing of direct temperature effects is performed by sensing radiation emitted from solids, liquids, and gases in the thermal infrared region of the spectrum. Thermal sensing of solids and liquids takes place in two "windows" of the atmosphere where absorption is at a minimum. The windows normally used are in the 4.2–5.1 μm and the 10.5–12.5 μm wavelength regions, although windows between 3 and 4 μm and a broader one, between 8 and 14 μm area, are also available. None of the windows is perfect because weak absorption by water vapor and carbon dioxide occurs and absorption by ozone affects the 10.5–12.5 μm interval (Short, 1996).

With the advent of thermal remote sensing, it has become feasible to undertake detailed analysis of landscape-scale surface temperature variability. Many of the world's remaining tropical forests exist in relatively inaccessible regions where it is not feasible to study forest canopy thermal budgets thoroughly using conventional micro-meteorological techniques (Luvall et. al., 1990). In such locations, remote sensing, and thermal remote sensing specifically, can serve as an excellent information source.

Thus, except for geothermal energy, man-made thermal sources, and forest fires, the immediate source of emitted thermal infrared radiation is shortwave solar energy. Direct solar radiation (with a peak at about 0.5 μm in the visible spectrum) is received and absorbed by the landscape. The amount and spectral distribution of energy emitted by landscape features depends on the thermal properties of these features, as discussed below. The contrasts in thermal brightness, observed as varied gray tones in a band 6 image are used as the basis for identification of features.

A 'blackbody' is an object that acts as a perfect absorber and emitter of radiation; it absorbs and re-emits all energy that it receives. Although the blackbody is an idealized concept, it is useful in describing and modeling the thermal behavior of actual objects.

As the temperature of a blackbody increases, the wavelength of peak emission increases in accordance with Wien's displacement law. The Stefan-Boltzmann law describes mathematically the increase in total radiation emitted (over a range of wavelengths) as the temperature of a blackbody increases.

Emissivity (ϵ_λ) is a ratio between emittance at a given wavelength (λ) from an object in relation to emittance from a blackbody at the same temperature:

$$\epsilon_\lambda = \frac{\text{Radiant emittance of an object}}{\text{Radiant emittance of a blackbody at the same temperature}}$$

Emissivity therefore varies from 0 to 1, with 1 signifying a substance with a thermal behavior identical to that of a blackbody. Some common emissivities are: sand at 20° C = 0.90, dry soils at 20° C = 0.92, wet soils at 20° C = 0.95, distilled water at 20° C = 0.96, and concrete at 20° C = 0.92. Many of the substances commonly present in the landscape (*e.g.*, soil and water) have emissivities close to 1. However, emissivity can vary with temperature, wavelength, and angle of observation.

Emissivity is a measure of the effectiveness of an object in translating temperature into emitted radiation (and in converting absorbed radiation into a change in observed temperature). Because objects differ with respect to emissivity, observed differences in emitted infrared energy do not translate directly into corresponding differences in temperature. As a result, it is necessary to apply knowledge of surface temperature, or emissivity variations, to study surface temperature patterns accurately from thermal imagery. Because knowledge of these characteristics assumes a detailed prior knowledge of the landscape, such interpretations should be considered appropriate for examination of a distribution known already in some detail, rather than for reconnaissance of an unknown pattern. Often, estimated values for emissivity are used, or assumed values are applied to areas of unknown emissivity.

2. Methods

2.1. The Study Area

In the study area (Figure 1) the vegetation is dry tropical forest. Along the coasts there are mangrove swamps, grassy shrublands, and tules (marshlands). In the northern portion of the peninsula, where it is drier and the soil is porous, the tropical vegetation ranges from scrublands to forest. Further south the vegetation becomes taller with fewer of the trees being deciduous. The peninsula is based on calcareous rock and there are no surface rivers, but rather there are many cenotes (large water holes) and underground rivers connecting these together. Rainfall in the region is heaviest during the summer months but does occur year round, and ranges from 20 " (500 mm) along the coast to 60 " (1500 mm) in the southern portions of the state. Mean temperatures remain high year-round, ranging from 70-90° F (20-30°C).

The image used in this analysis was taken on March 27th 1995 and is from the Landsat Thematic Mapper (Row 20, Path 46, Figure 2). Meteorological data from local climate stations are utilized to record large-scale temperature contrasts and precipitation events, which may result in localized flooding or pooled water. Localized precipitation events are much more difficult to determine from this (or any) data and are also spatially distinct, occurring over a limited area for short durations. No areas of precipitation were discerned across our study area for the week preceding the satellite image date. In addition, the image was taken at the end of the dry season, so surface effects relating to moisture differences are limited. Climate data reveal mean temperatures through the month of March of 70-80 °F (21-27 °C) with dew points around 50-60 °F (10-15.5 °C). The last measurable large-scale precipitation event across our study area occurred on March 17th and varied spatially from 0.2- 0.6 " (5-15 mm). Hence, the image for March 27th 1995 is ideal for our analysis as no large-scale precipitation event had occurred within the preceding 10 days. Precipitation can be a problem in thermal image analysis as differences in temperatures may relate to soils moisture differences not vegetation differences. To avoid such problems researchers always check images for precipitation in the days preceding image acquisition.

2.2.1. Image Calibration

Image calibration is necessary both for the thermal band and the reflective bands. The processes involved are slightly different and are described separately here. To calibrate band 6 it is necessary first to convert the digital number (DN) values to spectral radiance values L_λ (in mW cm^{-2} ster^{-1} µm^{-1}), which is accomplished with the following equation by knowing the lower and upper limit of the DN value range for a specific band:

$$L_\lambda = LMIN_\lambda + ..(\frac{LMAX_\lambda - LMIN_\lambda}{DNMAX})DN$$

where DN is the calibrated and quantized scaled radiance (digital numbers), $LMIN_\lambda$ is the spectral radiance at DN = 0, $LMAX_\lambda$ is the spectral radiance at DN = DNMAX, DNMAX is the range of rescaled radiance, and L_λ is the spectral radiance (Markham and Barker, 1986).

To convert the values from the recorded spectral radiance to the effective 'at-satellite' or apparent temperature (T_a in K) the following equation is used:

$$T_a = K1\frac{2}{\ln(K2\frac{1}{L_\lambda}+1)}$$

where K1 is 60.776 Kelvin (K), K2 is 1260.56 (in mW cm^{-2} ster^{-1} µm^{-1}), and L_λ is the spectral radiance (in mW cm^{-2} ster^{-1} µm^{-1}) (Markham and Barker, 1986).

To calibrate the reflective bands is a three-step process undertaken in order to allow us to compare the results of band 6 to the remaining bands. The first step converts the Landsat digital number values (DN_λ) to radiance values (I_λ). Step two converts radiance values to at-satellite exo-atmospheric reflectance ($R_{\lambda space}$). Step three converts the exo-atmospheric reflectance to effective at-surface reflectance factor (R_λ) (Markham and Barker, 1986). The different variables of satellite instrumentation, Earth-Sun distance, solar elevation angle, solar curve, and atmospheric effects are therefore eliminated as sources of variability and noise. While this calibration procedure is different for the thermal band than for the other bands, following the correct calibration procedures allows us to compare the values from all bands both visually and statistically.

2.2.2. Geo-referencing

Geo-referencing registered the image into Universal Transverse Mercator (UTM) coordinates, using 1:50,000 scale topographical maps of the study area, thus allowing cross-referencing of images across space and time.

2.3.1. Classification

Supervised classification using the Gaussian Maximum Likelihood technique was used to create seven classes: (1) urban/roads, (2) sink holes, (3) water/shade, (4) bare/soil, (5) irrigated agriculture, (6) early successional forest, and (7) late successional forest. These classes used training sample data obtained during the summer of 1998, provides detailed accuracy assessment of the results. These training samples were taken for each class used in the classification and for an area corresponding to the study area of the image, following the CIPEC protocol. Hence, for each training sample the land cover class, mean vegetation height, composition, structure, canopy closure and location are recorded. Of the 120 training sample points, 60 were used to create the initial land cover signatures, and 60 were used in the accuracy assessment.

2.3.2. Vegetation Indices

Studies conducted on temperate forests have successfully related biophysical properties with red and near-infrared radiance, particularly with the Normalized Difference Vegetation Index (NDVI). Boyd et al. (1996) also suggested that the relationship between forest biophysical properties and middle and thermal infrared radiance may be stronger than that between forest biophysical properties and visible and near-infrared radiance. Vegetation indices created for this analysis therefore were the basic NDVI analysis, a Tasseled Cap Transformation analysis, and a number of thermal based vegetation indices.

The NDVI is created through a ratio of the TM bands three and four using the equation: $NDVI = (TM4 - TM3) / (TM4 + TM3)$. NDVI was one of the first successful vegetation indices created based on band ratioing. However, in many tropical environments, researchers have found less than satisfactory results between NDVI and ground-based measures of vegetation (Boyd et al., 1996). Since the development of this initial vegetation index, many more indices have been created and researchers have attempted to relate these indices to different land cover or vegetation characteristics. One such index is the tasseled cap transformation developed by Kauth and Thomas in 1976, originally created with Landsat MSS data. The analysis identifies six new axes (using Landsat TM data bands 1-5, and 7). The first two axes represent soil brightness as a 'brightness index', and green vegetation as a 'greenness index'. The third axis is believed to relate to moisture and the fourth to haze, but these have only been tested in a limited capacity with TM data. Hence, in this analysis most of the attention is on the first two bands created: brightness and greenness.

In addition to these more commonly used vegetation indices, a number of less common or newly created indices also were used. All of these indices used the temperature image data created from the raw band 6 information and are referred to as TM6. The vegetation indices are: (1) TM6/(TM3 + TM5), (2) (TM2 – TM6) / (TM 2 + TM 6), (3) (TM2 * TM6) / TM7, (4) TM6 / NDVI, (5) GREENNESS * TM6, and (6) (B4 * B7) / B6. The first three of these indices were taken from Boyd et al., (1996) and the latter three were created for this analysis. Other researchers have illustrated that using band 6, or the effective radiant temperature values in vegetation analyses can be related to biophysical properties, canopy structure, and species information (Luvall et al., 1990; Boyd et al., 1996). Hence, in this research some of these previously used indices and three new indices were created. Most previous research has only utilized the band information from the image whereas in this work actual indices are used (e.g., greenness index, NDVI) in combination with band 6 in an attempt to expand on previous work. All of these different vegetation indices will be evaluated in terms of their relationships with the land cover classification image and with each other.

2.3.3. Surface Temperatures of Land Cover Classes

Large-scale conversion of tropical forests into pastures or annual crops will likely lead to changes in the local microclimate of those regions. Larger diurnal fluctuations of surface temperature and humidity deficit, increased surface runoff during rainy periods, decreased runoff during the dry season, and decreased soil moisture are to be expected (Salati and Nobre, 1991). An example of changes in the microclimate would be the change in surface albedo (reflectivity) of an area following deforestation. The surface albedo is calculated as the ratio of reflected radiation to that of the incident solar radiation. This value measures the amount of energy absorbed by the surface, and hence available to heat the air above, as most reflected radiation is lost to space. An area of dense forest cover will have a much lower albedo than an area of soil or shorter vegetation, which means the forested area will absorb more radiation and reflect less and hence have more energy available to it (Dickinson, 1981).

Canopy microclimate is ultimately determined by the stand micro-climate; the rhythms of change above and within the forest are set by the cycles of annual and diurnal heating and by the movements of air masses and clouds (Parker, 1995). The relevance of satellite-derived surface temperature values for studies of forest microclimate depends largely on the relationship between temperature at the canopy and that within the forest. Satellite derived temperatures correspond to surface temperature which, in a forest zone, is represented by the temperature at the top of the canopy (Nichol, 1995). Within the dry topical forest region under study a cooler temperature means a denser and more mature forest. This relationship does not hold true for all forest types e.g., some tropical moist forest areas where secondary successional forests are denser in terms of vegetation amount than the more mature forest.

Mature closed canopy forest may be expected to be cooler than immature forest with an open canopy due to a high leaf area index and efficient water uptake from a well-developed root system in a mature soil. This will increase the latent heat flux (Q_E) and hence decrease the sensible heat flux (Q_H) so temperatures are cooler. So within a tropical forest environment the canopy effectively regulates canopy temperature, which is a useful indicator of forest microclimate (Nichol, 1995). Hence, the differentiation of forest age or successional class should be possible using band 6 data.

In this analysis, the band 6 raw data were calibrated to at-sensor apparent temperatures (T_a in K) and, using these values and the known surface and vegetation emissivity (ε) values, the surface temperatures (T_s in K) can be calculated:

$$\varepsilon \sigma T_s^4 = \sigma T_a^4$$

where σ is the Stefan Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}) and emissivity is an average value for the land cover class (Nichol, 1995). Using this formula, surface temperatures for the study area can be obtained. Such data allow the spatial mapping of surface temperatures and the relations between the calculated surface temperatures, information from different bands, and the land cover information can all be analyzed together. This provides a much larger data source, which can usually be obtained quickly and provides an excellent starting point for all LULCC studies. Using this information, the actual surface temperatures can be compared for each land cover class and the apparent (blackbody) temperatures can be created for the image as a whole. This analysis allows us to evaluate the land cover classes in terms of their biophysical and meteorological properties.

2.3.4. Statistical Analysis of the Land Cover Classification

The dependence of surface temperature on the magnitude of biomass can be evaluated statistically by correlating the thermal band image data with any vegetation index, such as NDVI or the Tasseled Cap Transformation variables, such as greenness. This was done for the image area by converting the image bands into an ASCII dataset, which could then be imported into a statistical package for analysis. Hence, the dataset for comparison of the bands and information content is composed of thousands of data records each relating to a single pixel on the image. All of the analysis discussed here is based on this dataset.

A correlation matrix was calculated and this illustrates the interrelationships between the reflected bands (bands 1-5,7). Thermal band data are gathered from a different instrument, making the relationships with band 6 statistically meaningful since they are not merely a function of the measurement process. In addition, the information from the seven bands of Landsat TM data was correlated with the main vegetation indices discussed, as well as with the classification analysis results, to evaluate the strengths of the various relationships.

A discriminant function analysis was used to determine the relative importance of the different radiances, emissions, and indices, provided by all of the analyses, in discrimination of the land cover classes. The Wilks's lambda coefficients were used to determine the relative importance of the different information layers as discriminating variables of land cover. The magnitude of the lambda coefficient is inversely proportional to the ability of an information layer to discriminate between the classes (Boyd et al., 1996).

3. Results

3.3.1. Classification

Supervised classification using the Gaussian Maximum Likelihood technique was undertaken using the spectral signatures created from the training sample data. From this dataset half were used for creating the class signatures for the classification and half were held back for use in the accuracy assessment process. From this second set of data the accuracy of the created classified image was evaluated using the remaining training samples. The results of this accuracy assessments for both of the classifications, the first using bands 1-5, and 7 (Figure 3), and the second classification using all 7 bands (Figure 4), are the same with an overall classification accuracy of 96.1 % and an overall Kappa Index of 0.95. The addition of band 6 data did not improve the classification accuracy statistically, but did improve the overall appearance of the classified image. Adding band 6, while not impacting the overall accuracy of the classification procedure, smoothes the surface in a manner similar to running a 3 x 3 filter pass over the image (Figure 4). Since most post-classification methodologies do a filter pass to smooth the surface as an extra step after classification, the inclusion of band 6 in the classification procedure allows us to incorporate this step into a single method. This saves time and produces a more meaningful result, as rather than simply smoothing by a statistical averaging window, we are smoothing by temperature surfaces, which directly relates to ground cover.

3.3.2. Vegetation Indices

The Tasseled Cap Transformation index was one of the most useful in this analysis. The study area can be illustrated using the brightness, greenness, and moisture axes of this analysis and this appears to capture much of the image variability in only three bands of information (Figure 5). The Tasseled Cap Transformation is an excellent data reduction technique, without much loss of relevant data, in addition to providing information on soils, vegetation, and moisture content across the image area.

3.3.3. Surface Temperatures

In our study area distinct spatial variations in thermal characteristics are evident from the apparent (blackbody) temperatures and are clearly observed to correspond to land cover differences (Figure 6). Mature forest has the coolest temperatures and cleared, bare soil has the highest temperatures of the natural surfaces, with urban/roads having the highest temperatures overall. In addition, when including the effect of surface emissivity to calculate surface temperatures, these differences become even greater across land cover types (Table 1). Hence, differentiation of forests based on successional stage is feasible. The spatial variability of temperatures across the image (Figure 6) clearly illustrates the utility of this temperature based information layer. In addition, the close relationship between temperatures and land cover class (Table 1) highlights the importance of the information in this image band.

When comparing the classification undertaken using bands 1-5, and 7 (Figure 3) versus the temperature coverage (Figure 6), there is a noticeable similarity to the coverages. This is of particular interest given the amount of information available for the classification procedure: bands 1-5 and 7 not only contain 16 times more information due to their 30 m by 30 m resolution (compared to band 6 resolution of 120 m by 120 m), but also all six bands are used in combination for the analysis (compared to only one band for the band 6 classification).

3.3.4. Statistical analysis of different band contributions to the classification analysis

A correlation matrix (Table 2) computing Pearson's correlation coefficients shows that only band 4 appears significantly uncorrelated with the remaining bands. Temperatures are strongly correlated with bands 7, 5, and 3, all of which are used in vegetation analyses. The thermal band has a positive linear relationship with all bands except for band 4, which shows a negative linear relationship, though this relationship is quite moderate (Pearson's correlation coefficient = -0.58). Given the differences in band resolution of 16 pixels to every band 6 pixel, these relationships appear to be quite impressive. Due to the large number of data points included in the statistical analyses (the study area was converted from a raster image to an ASCII file with more than 100,000 data points) the statistical significance is irrelevant. All relationships discussed here are statistically significant at the 0.99 level of significance.

The correlation matrix also reveals the relationships between the TM bands the Tasseled Cap Transformation images of brightness, greenness, moisture and haze, the NDVI, and the land cover classes. I found a correlation of 0.98 between the Tasseled Cap Transformation greenness index and the NDVI, indicating that for this tropical dry forest ecosystem these two separate indices are therefore both measuring identical conditions. The temperature data have strong correlations with greenness (-0.80), moisture (-0.88), band 3 (0.77), band 5 (0.83), band 7 (0.85), and NDVI (-0.83). The temperature data also have a fairly strong relationship with land cover class (-0.56). Thus, our land cover classes appear to have strong correlations with a number of our individual information layers.

A comparison between NDVI vegetation index and blackbody temperatures indicates a close spatial correspondence between temperatures and land cover type. The dependence of T_a (and hence T_s) on biomass was tested by regressing the band 6 blackbody temperature image data with the NDVI vegetation index image data. A regression of NDVI and blackbody temperatures results in a negative relationship with increasing vegetation amounts producing a higher index value, and corresponding to cooler temperatures (Figure 7). I found an adjusted r^2 value of 0.70 between temperatures and NDVI. This relates well to previous research and again highlights that the temperature values relate to the vegetation cover. The pattern of high NDVI equals cooler temperatures, which relate to irrigated agriculture (Figure 7). As NDVI decreases and temperatures increase, the pattern of land cover changes from mature forest, to mid-to-early successional forest, and then to soils or bare earth. Urban/roads have the lowest NDVI values and the highest temperatures (Figure 7). This clearly illustrates the close relationship between NDVI, temperature, and land cover classes.

A comparison of some of the vegetation indices illustrates the location of temperatures within the NDVI/Brightness space (Figure 8(a)) and within the Brightness-Greenness space (Figure 8(b)). This unique way of plotting the data illustrates the relationships between these variables quite clearly. Within the analysis of NDVI and temperatures, as discussed above, there is now included a third variable. Hence, a high NDVI and low brightness value both indicate cooler temperatures. As brightness values increase, temperatures increase. In addition, higher values of greenness indicate cooler temperatures. These perspectives (Figures 8(a) and (b)) allow us to determine more accurately the existing relationships, and also allow us to see the value of our temperature analyses, which so plainly differentiates the land cover type, despite its much coarser resolution.

For all the indices and band information used in this analysis, the relative strengths of the relationships between land-cover classes and the different information layers were evaluated. The Wilks's lambda coefficients (Table 3), as determined from the discriminant analysis, are used to determine the relative importance of the different bands of information and vegetation indices as discriminating variables for land cover analyses. The magnitude of the lambda coefficient obtained is inversely proportional to the ability of the information layer to discriminate between the land cover classes (Boyd et al., 1996). Here the rank order of the individual information bands and indices (Table 3) illustrates that data acquired by band 6, while not the most significant of all the information layers, is one of the more important, with a lambda coefficient of 0.354. The most significant information layers are NDVI (0.181), greenness (0.183), greenness*TM6 (0.188), band 4 (0.257), TM6 / (TM3+TM5) (0.270), band 7 (0.274), and (TM2*TM6) / TM7 (0.279). Of the top seven information layers, three include band 6 information.

Also of interest the vegetation indices created here frequently outperform the individual Landsat TM bands in classifying land cover. It appears from this research that the incorporation of the individual TM bands into vegetation indices acts to enhance their information content and thus increase the strength of the relationships with land cover. The inclusion of these bands into vegetation indices strengthens the reported correlations.

4. Discussion

Satellite-based thermography offers an accurate, useful, novel, and viable means of monitoring forest environments and estimating spatial aspects of the forest energy budget. The inclusion of band 6 data within vegetation indices significantly increases the strength of the relationships between radiance values and land cover classes of dry tropical forests. Therefore, the potential for incorporating band 6 data into land cover analyses is great. Specifically, the incorporation of band 6 into actual classification procedures and vegetation indices is recommended both using Landsat 5 and 7 satellite products. The data obtained using thermal band information from Landsat 5 is at a resolution 16 times greater than that of the reflective bands. But this single band provides an immense amount of information. Other reflective bands must be used in combination to maximize accuracy and usefulness.

In a study undertaken in the Singapore Central Catchment Area Nature Reserves, Nichol (1995) found distinct spatial variations in thermal characteristics (using Landsat 5, band 6), which were observed to correspond to land-cover differences relating to forest, urban, water, and suburban areas. Differences also were noticed in the temperatures calculated for areas of forest, corresponding to primary and late secondary succession. These coolest areas are buffered in most instances by a broad belt of slightly warmer forest or water. Cool interior forest polygons were surrounded by slightly warmer forest polygons rather than non-forest. Additionally, within the analysis, small interruptions in the forest canopy were detected as points or ridges of higher temperatures. Such results indicate that differences within vegetation types, and specifically across different successional stages, can be picked up by thermal analysis. The dependence of surface temperature results on biomass was also tested in this research by correlating the thermal band emissivity corrected image data with NDVI using a random sample of 2000 pixels (excluding water). A Spearman's rank correlation coefficient of 0.74 between temperature and biomass was found.

Lambin and Ehrlich (1996) argued that the use of such remotely sensed variables as measurements of thermal infrared radiation or derived surface temperatures may be as important as the many vegetation indices used in much of today's research. Indeed, they found that the combination of thermal band information with vegetation indices improved the mapping and monitoring of land cover at broad scales. They found a combination of vegetation indices, a thermal measure, and seasonality (if relevant) produced the best results in terms of land cover analyses.

Mauser and Schädlich (1998) found that NOAA Advanced Very High Resolution Radiometer (AVHRR) thermal data could be used to differentiate land cover types. Their research demonstrated the mesoscale heterogeneity of the region under study, revealing landscape-like units relating to cities, forest, lakes, and agricultural areas. They found a correlation of 0.80 ($p = 0.99$) between evapotranspiration and temperatures.

Thermal remote sensing has also been used by a number of researchers to determine meteorological data for energy balance models (François et al., 1999; McVicar and Jupp, 1999; Mauser et al., 1998; Snyder et al., 1998). This method allows for the derivation of specific time-of-day components of the energy balance at the time of the remotely sensed data acquisition. McVicar and Jupp (1999) found that climate station data, which includes maximum and minimum temperatures and daily precipitation, can be accurately linked with thermal remote sensing (either Landsat or AVHRR data). As such this data can be used to increase the spatial density of meteorological stations, thus allowing better determination of the spatial energy balance. François et al. (1999) compared the minimum air temperature to the thermal band satellite based surface temperature and found a very strong (and statistically significant) correlation between the two.

5. Conclusions

The main objective of this research was to evaluate Landsat TM thermal data for use both as a stand-alone data set to produce preliminary, broad scale land cover analyses and as a supplement to other sensor information. From the thermal band data it is possible to derive surface temperatures. This is useful in micro-meteorological studies, especially in more remote areas where meteorological data of an appropriate spatial distribution is rare. It is an excellent data source when used in conjunction with the other image bands (e.g., in color composites and vegetation analyses), and can reveal otherwise concealed information.

The thermal band information can also be used in conjunction with maps and other regional information as a verification tool. These data are measured by a different system than the reflective bands, allowing us to have a completely separate data source for use in analyses in which we know the sensors are 'seeing' and recording information for the same pixels. This is especially useful for remote areas where fieldwork is not feasible due to financial or logistical limitations. The thermal band information may be used in association with the other TM bands when actual field verification is not feasible, timely, or cost-effective. The use of the thermal band data has immense potential as both a stand-alone data set and as a verification tool.

One of the main arguments against using band 6 data relates to its coarser spatial resolution compared to the reflective bands. However, the spatial resolution of thermal data on the Landsat 7 satellite is 60 m by 60 m and so it is necessary to start to use and understand this data source now. Future improvement in resolution will only enhance and expand current uses of this data set.

The following conclusions were drawn from the results of this research:

1. Pearson's correlations were calculated between all information layers and land cover classifications, verifying the usefulness of band 6 data both as a single data layer and for use in vegetation indices.
2. Discriminant analysis revealed that band 6 data contains considerable information for the discrimination of land cover classes in the dry tropical forest ecosystem of Yucatan, Mexico.
3. For the best results in remote sensing analyses of land cover change, multiple data sources should be used in order to achieve a comprehensive description of surface processes. To do this both reflective and emitted data sources and image products must be used together.

It is evident that thermal remote sensing is potentially a powerful tool for examining forest canopy thermal responses on a landscape scale, and is particularly suited for use in tropical forests where access is difficult. Clearly, knowledge of the spatial distribution pattern of significant aspects of forest energy budgets and vegetation patterns will contribute to our understanding of the determinants of these processes, enhancing our ability to model such processes over landscape scales (Luvall et. al., 1990). This is essential within the research arena of global change where we must better monitor and explain current patterns of land cover in order to better determine potential future change. As such, for both climate and vegetation based research, band 6 temperature data is an increasingly important component in remote sensing research.

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Table 1: Comparison of surface temperatures for each land cover class for image and field based measures

Class	Measured field temperature * (°F)	At-Satellite blackbody temperature (°F)	Land cover emissivity (Oke, 1987)	Calculated actual surface temperature (°F)
Water	N/A	73-77	0.97	75.3 - 79.4
Agriculture	N/A	78	0.94	78.8
Mid-to-late Succession	89-93	79-81	0.99	79.8 - 81.8
Early-to-mid succession	93-96	82-84	0.98	83.7 - 85.7
Bare earth	96-110	85-91	0.95	89.5 - 95.8
Urban/roads	106-120	92-97	0.92	100.0 - 105.4

* I took field measures of temperatures to determine if the pattern of values is similar to the calculated surface temperatures using the satellite data. However, these field measurements were taken in a different year and in a different season; thus, the values do show the same pattern but are not the same as the satellite measured values.

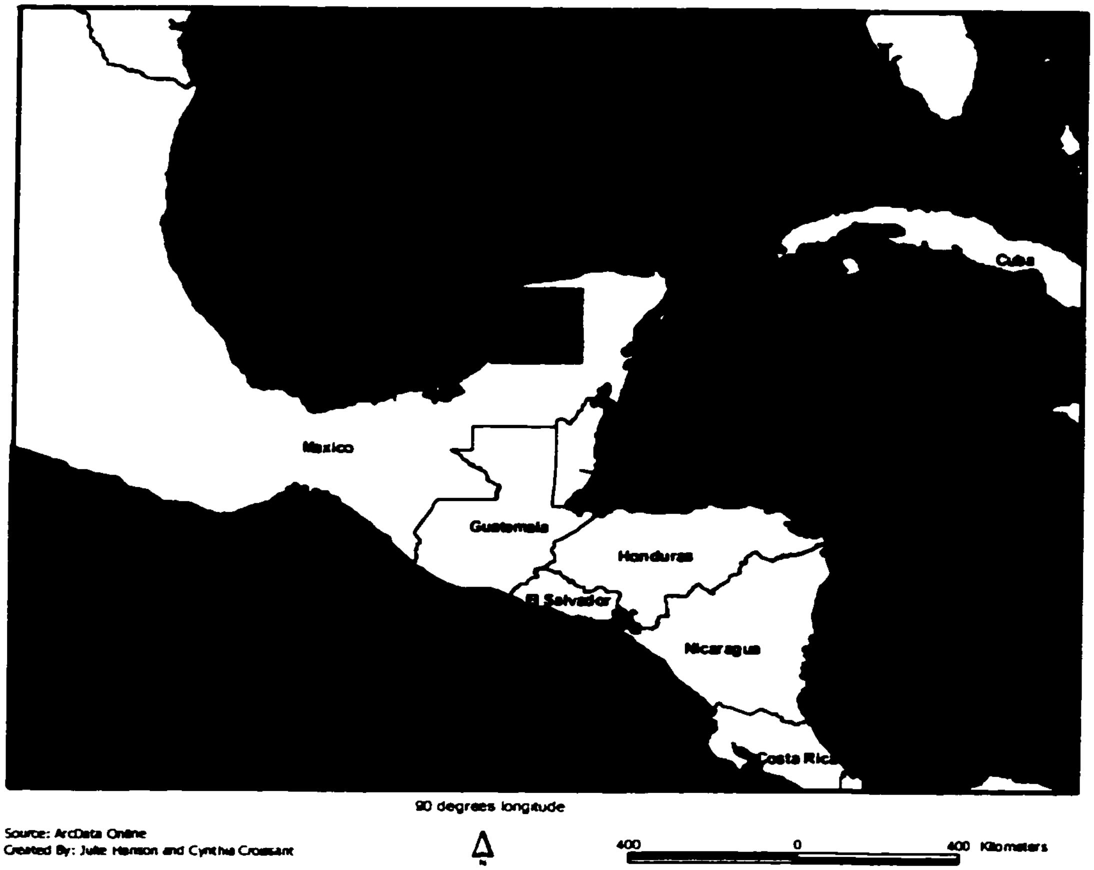
Table 2: Correlation matrix of the reflective bands, temperatures, tasseled cap and NDVI vegetation indices, and land cover class.

	bright	green	moist	haze	temp	b1	b2	b3	b4	b5	b7	NDVI	Class
bright	1.00												
green	-0.31	1.00											
moist	-0.61	0.89	1.00										
haze	-0.59	0.63	0.74	1.00									
temps	0.55	-0.80	-0.88	-0.68	1.00								
band 1	0.83	-0.60	-0.69	-0.41	0.64	1.00							
band 2	0.89	-0.31	-0.47	-0.47	0.45	0.85	1.00						
band 3	0.83	-0.74	-0.83	-0.77	0.77	0.90	0.81	1.00					
band 4	0.16	0.88	0.66	0.38	-0.58	-0.18	0.15	-0.34	1.00				
band 5	0.83	-0.73	-0.94	-0.76	0.83	0.80	0.68	0.90	-0.38	1.00			
band 7	0.78	-0.81	-0.96	-0.75	0.85	0.82	0.67	0.92	-0.47	0.97	1.00		
NDVI	-0.40	0.98	0.91	0.71	-0.83	-0.63	-0.37	-0.80	0.82	-0.78	-0.85	1.00	
Class	-0.67	0.40	0.61	0.57	-0.56	-0.56	-0.51	-0.65	0.11	-0.69	-0.68	0.51	1.00

Table 3: Results from the discriminant analysis, to determine the ability of each information layer to distinguish land cover class.

Image layer / Vegetation Index	Wilks' Lambda
Band 1	0.519
Band 2	0.635
Band 3	0.355
Band 4	0.257
Band 5	0.305
Band 7	0.274
Temperatures	0.354
Tasseled Cap: Brightness	0.504
Tasseled Cap: Greenness	0.183
TM6/(TM3+TM5)	0.270
(TM2-TM6)/(TM2+TM6)	0.743
(TM2*TM6)/TM7	0.279
NDVI	0.181
TM6/NDVI	0.556
Greenness * TM6	0.188
(B4*B7)/B6	0.559

Figure 1: Overview of the Yucatan study area and satellite image location



Source: ArcData Online
Created By: Julie Hanson and Cynthia Croissant

Figure 2: Landsat TM 3,4,5, composite image of the study area

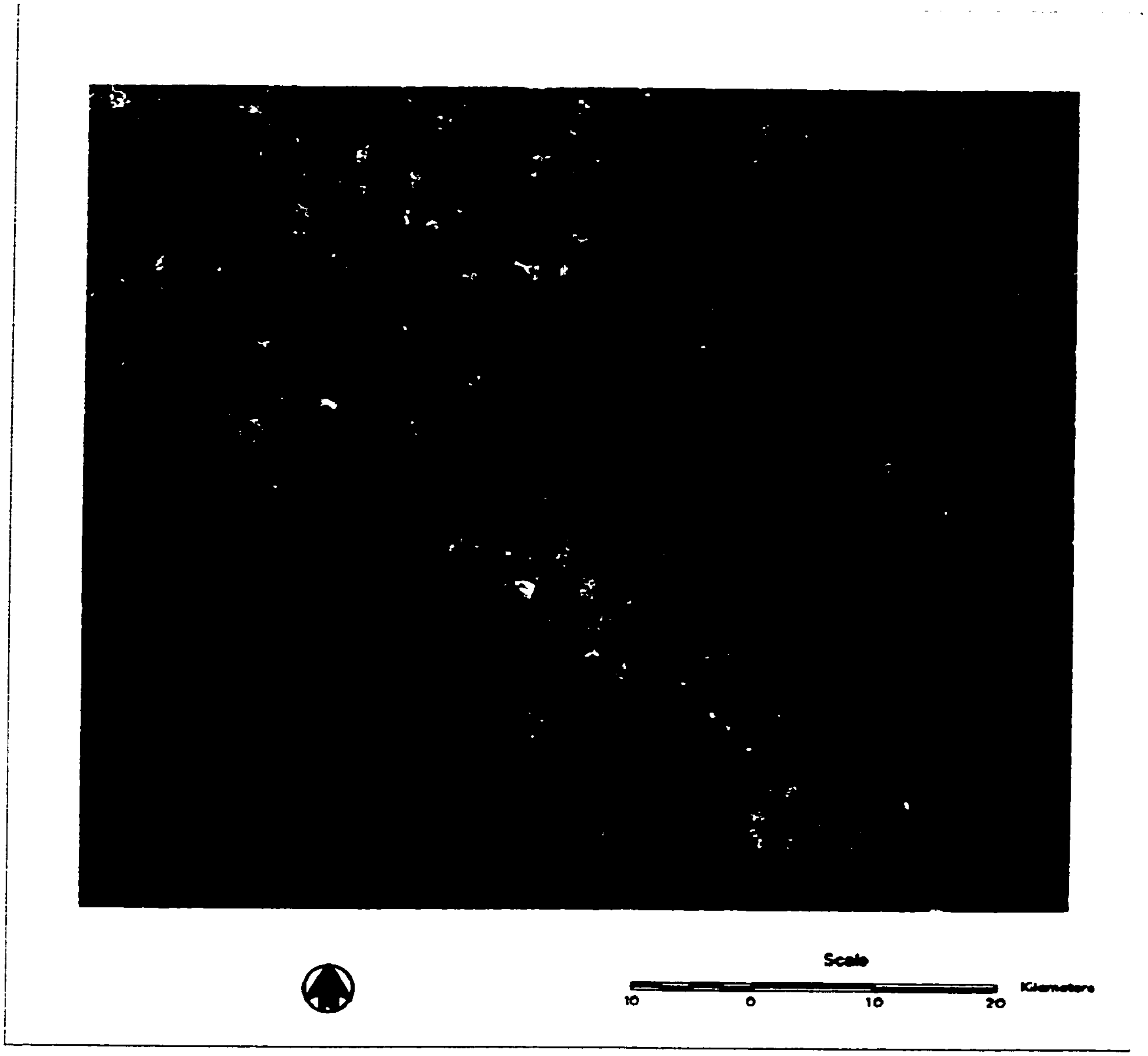


Figure 3: 7 class supervised classification using bands 1-5,7

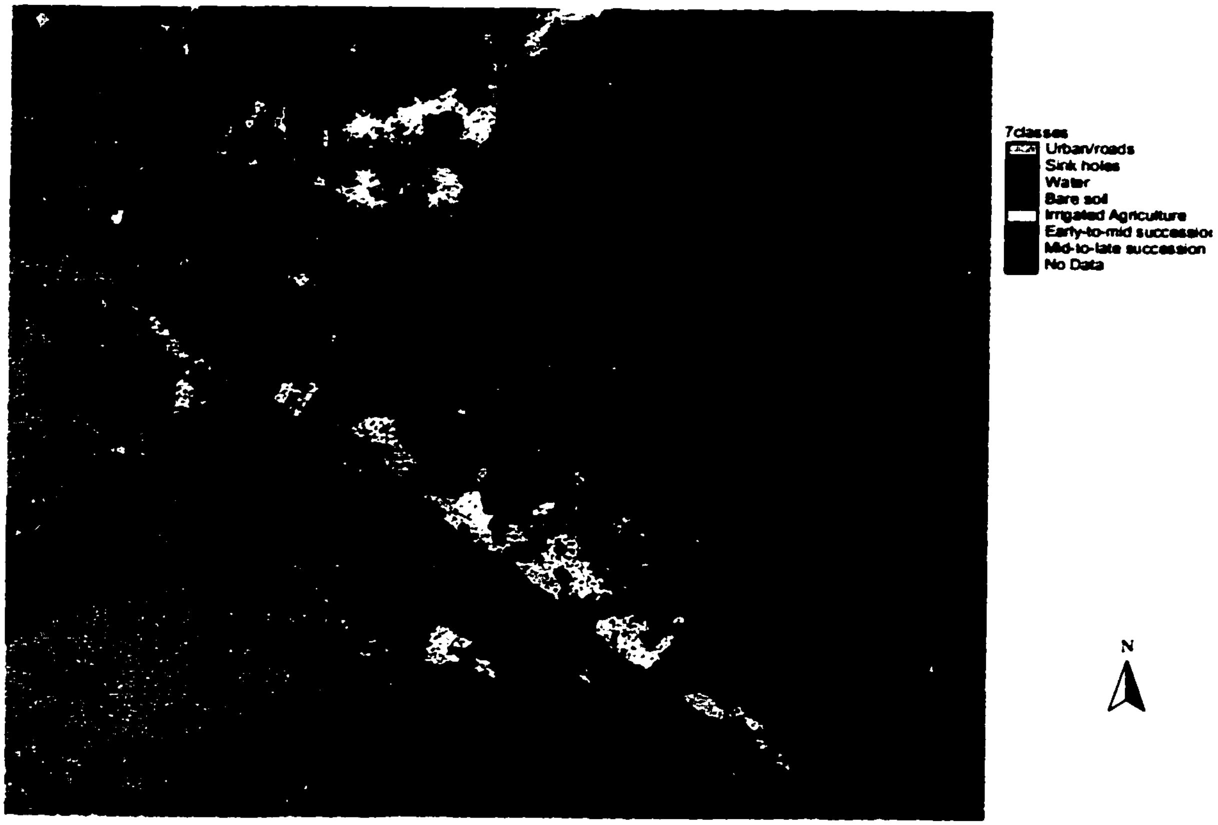


Figure 4: 7 class supervised classification based on all 7 TM bands

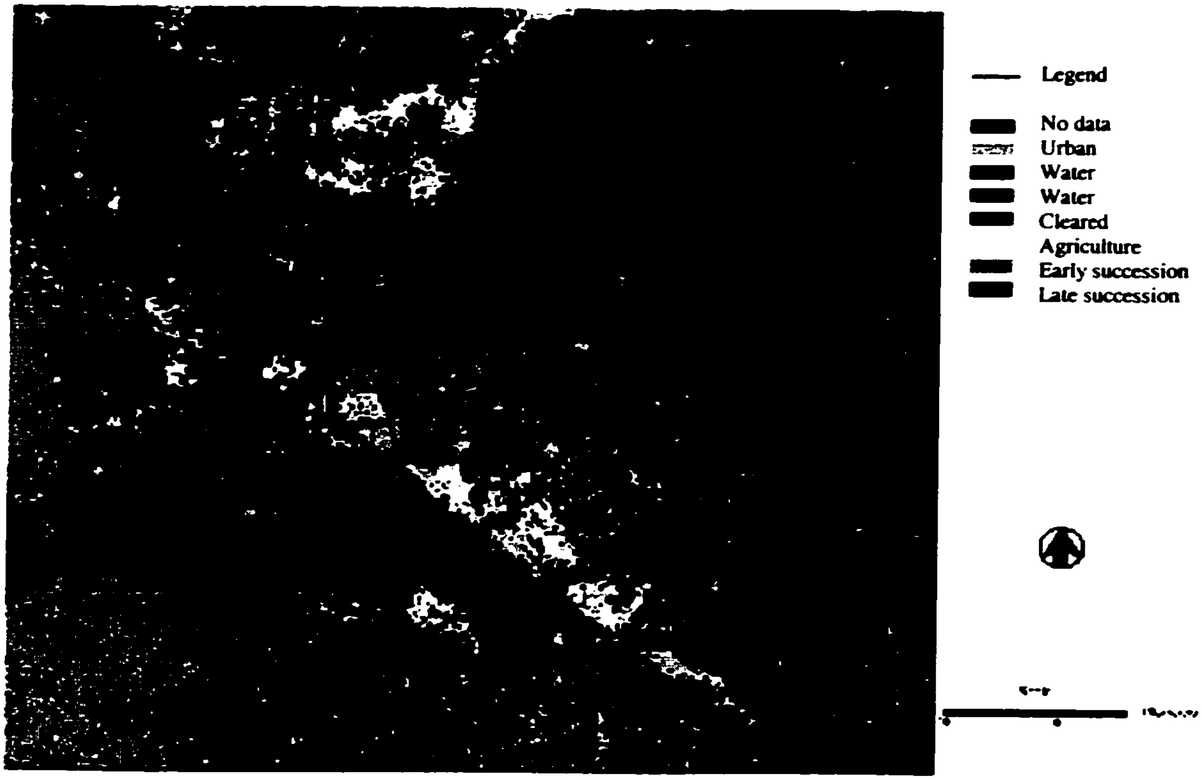


Figure 5: Tasseled Cap Transformation Analysis: Brightness (red), Greennes (green), and Moisture (blue)

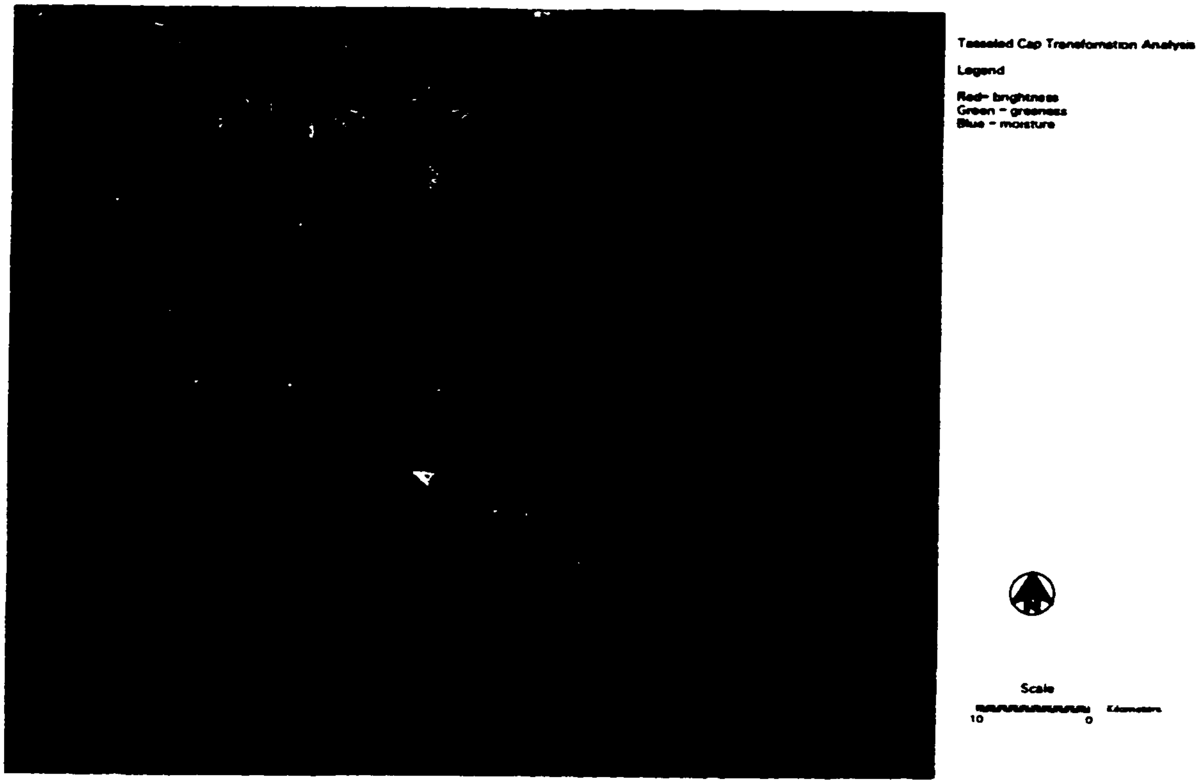


Figure 6: Temperature coverage of the Yucatan study area

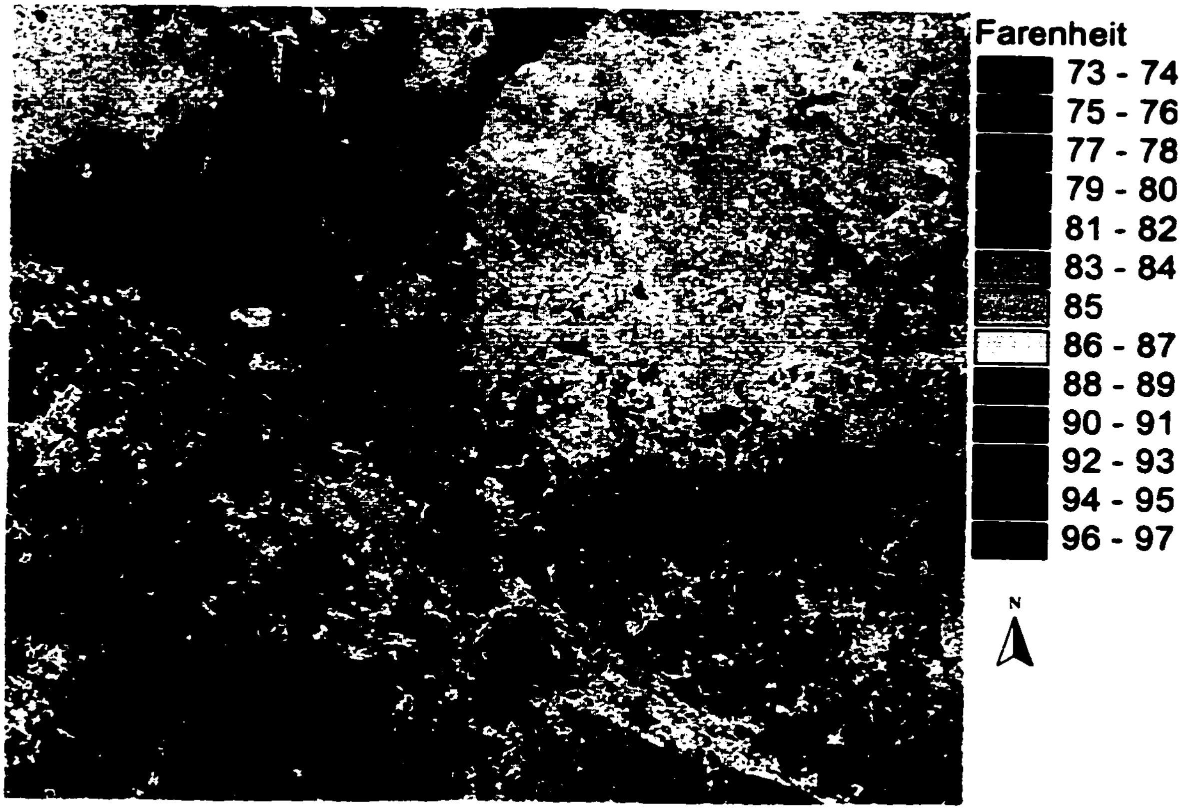


Figure 7: NDVI versus temperatures with colors representing land cover classes. Where yellow = irrigated agriculture, dark green = mid-to-late succession forest, lighter green = mid-to-early succession forest, orange = soil and bare earth, and light blue = urban and roads

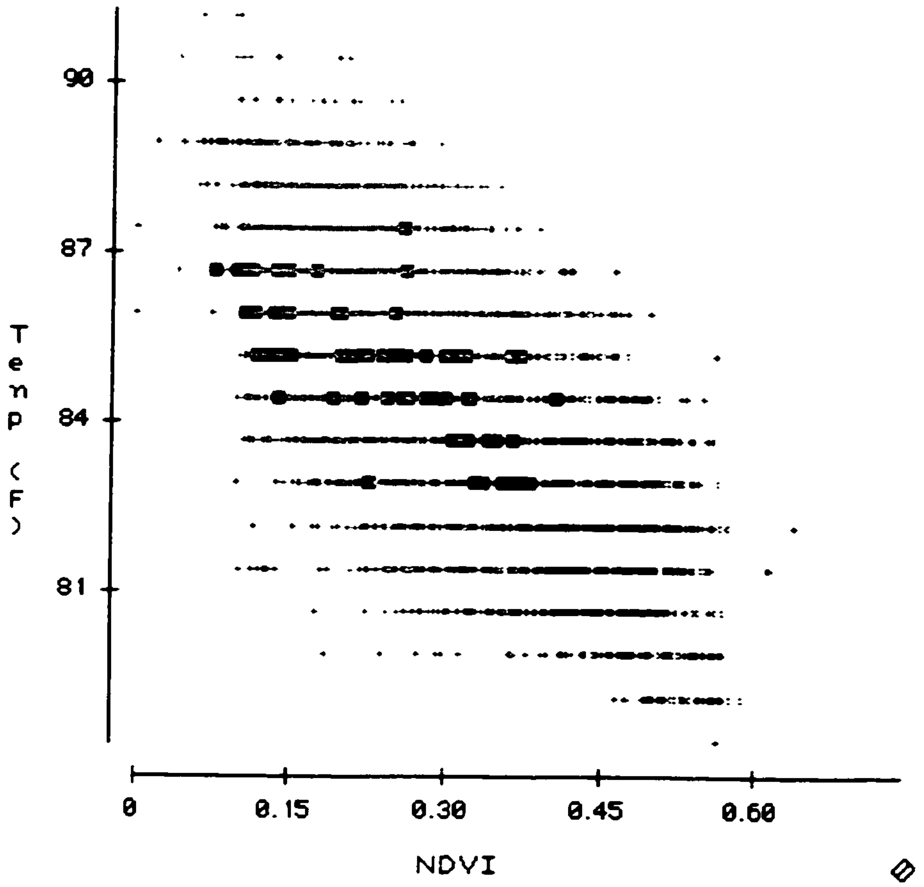
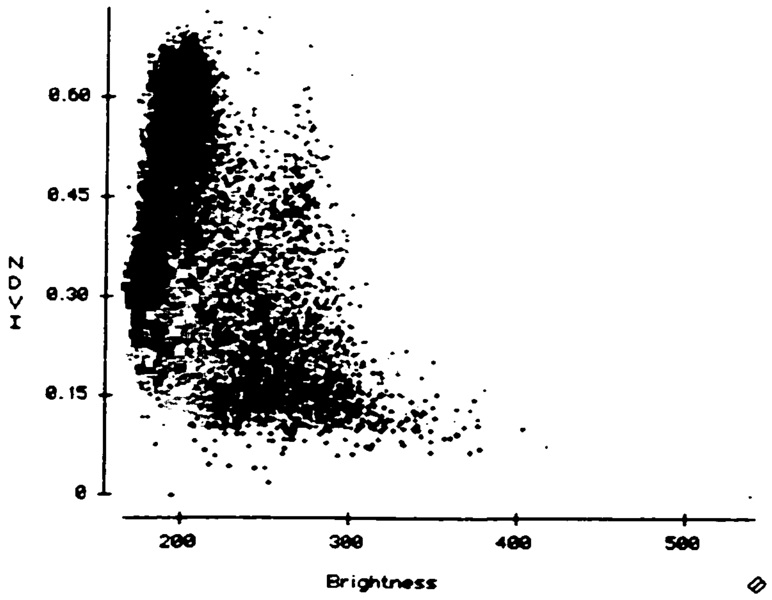
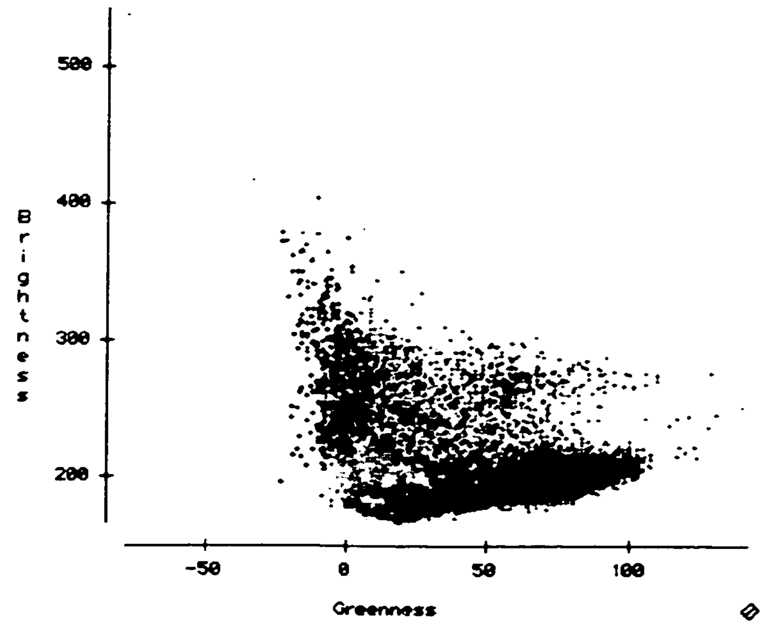


Figure 8: Vegetation indices with (a) NDVI versus brightness, and (b) brightness versus greenness, with colors representing temperatures. (Red = hottest, through orange, yellow, green, to blue = coolest)

(a)



(b)



Chapter 7:

Conclusions

In discussion of future research needs and challenges for the scientific community much attention is paid to the issues of climate change and human induced land-cover change, in terms of causes, rates, and implications. These issues are raised as prominent research areas in the new millennium, and areas where there is a need for greater monitoring, modeling, and understanding of the processes at work (USGCRP, 1998). If we are to limit the potential impacts from land cover change and future climate changes on our global environment, we must have a sound scientific understanding of terrestrial ecosystems, their change processes, and their interactions with global change. This has been the fundamental goal of this research.

The overall objective of this research was to understand more fully the processes and potential impacts of land cover change and future climate change on our environment. The research presented in this dissertation was divided into several topics, which, while strongly interconnected within the theme of global change, also have separate research questions associated with them. Implications of this work for the wider scientific community and future plans will also be discussed.

Topic 1: Climate change and changing climate variability impacts on maize production in the Midwest United States.

The primary objective of this research was to identify the potential impacts of climate change and changing climate variability on agriculture in the Midwest region of the United States. Chapter Two described in detail the methods used and the climate scenarios created for this analysis. Chapter Three applied these models and techniques to the growth of maize at ten site-specific locations and addressed the following questions:

1. How sensitive are current maize growing agricultural systems to different scenarios of future climate change?
2. What are the additional impacts on site-specific maize growth relating to changing climate variability?
3. Which areas gain and which areas lose under these future climate scenarios?
4. What are some potential adaptation strategies for this region?

The primary conclusions from this section of the research were:

- A growing season dominated by a central period of high maximum daily temperatures is a critical inhibitor to maize yields. Late spring and early fall frosts do not affect maize yields. Hence, HadCM2-GHG scenarios were those most detrimental to maize growth and the halved variability and sulphate scenarios (HadCM2-SUL) produced the best conditions for maize growth.
- Climate variability is a significant factor influencing maize yields because increased climate variability results in the largest decreases in future maize yields.
- The north-south temperature gradient in the Midwestern Great Lakes states is extremely important in influencing patterns of maize yield under future climate conditions. Areas in the south of the study area produced the greatest yield losses and northern areas had the highest yield increases for all scenarios.
- Some possible adaptations are: (1) the development of a more heat tolerant hybrid of long-season maize and (2) switching from maize (a C_4 crop) to soybeans or wheat (C_3 crops) to take advantage of increased atmospheric CO_2 concentrations.

This will act to promote increased growth and greater tolerances for hot temperatures (although how realistic this may be will be dependent on market factors). In addition, improving soils moisture management will become of increasing importance.

2. Climate change impacts on forests in the Midwest United States

The overall objective of this research was to examine the possible transient responses of tree species of the Southern Great Lakes Region to a 2 x CO_2-changed climate scenario. Specific questions addressed in Chapter Four were:

1. How will the changed climate scenario affect total basal area of each tree species studied in terms of their spatial extent?
2. How will the resultant regional population centers of the tree species respond to the changed climate?
3. Which species will thrive, which will die out, and how will this vary spatially?
4. What will the likely forest assemblages be in 2080 for this study area and where will the main shifts in forest type occur?
5. What are the implications for these changes when considering current land use in this region and the likelihood of such future changes in forests?

The primary conclusions from this research were:

- The effect of climate change on northern conifers and northern deciduous species was an almost complete loss of the species, greater than 99% decrease. The total basal area of intermediate and southern species increased slightly under the effects of climate change, by 1.2% and 0.3% respectively.

- Northern conifer population centers shifted 252.6 km northwest under changed climate conditions. Northern deciduous species shifted 140.2 km northeast, Intermediate species shifted 22.4 km east, and southern species shifted 32 km northeast.
- Under changed climate conditions regional population centers of white oak, pignut hickory, black oak, and northern red oak all shifted eastward. Sugar maple and American beech moved northeast and sugar maple was virtually eliminated.
- Most of our study area presently is a transition zone where species typically found in beech-maple communities occur on cooler, moister north- and east-facing slopes and species found in oak-hickory communities occur on warmer, dryer south- and west-facing slopes. Climate change may result in a shift to oak-hickory forests as dominants throughout the study region.
- Those species at the southern limits of their ranges, the northern conifers and northern deciduous species, were almost completely extirpated from the study region. The effect of the changed climate on intermediate and southern species was negligible.

3. Land cover change in Honduras and Guatemala

The main objective of this research was to identify areas of deforestation and reforestation within the study area and to address the potential impacts of such changes on land cover in western Honduras. Specific questions addressed in this research are:

1. What are the amounts of deforestation and reforestation occurring across the study area?

2. What are the dominant causes of these changes in land cover and the implications of such changes for the focus region?
3. How do the patterns of accessibility vary spatially across the region, and how do these relate to forest change?
4. How does land-tenure impact forest cover within La Campa?

The primary conclusions from this research were:

- At the level of the entire TM scene, which includes western Honduras and eastern Guatemala, deforestation is the dominant trend in forest cover change from 1987 to 1996. At the scale of western Honduras, we found regrowth to be the dominant trend.
- The changing local institutions within La Campa have resulted in an increase in forest cover, in addition to the broader patterns of forest regrowth linked to agricultural intensification, land abandonment, and natural regeneration of overexploited pine forests.
- Spatial patterns of change relate to accessibility and tenure, with greater accessibility leading to more clearing, and communal forests having higher rates of deforestation than private forests.
- Future increase in deforestation is likely due to increasing population pressure (high fertility rates), and expanding coffee production with associated forest clearing.

4. Implications of band 6 thermal data on land cover classification techniques.

The overall objective of the research was to integrate thermal band imagery analysis into vegetation land cover analysis methodologies and to assess the impacts of including such data within traditional analysis techniques. Specific research questions addressed in Chapter Six were:

1. How effective is the thermal band information for vegetation studies of successional change?
2. What additional information is provided by thermal band information when it is included in vegetation studies?
3. How can the use of the thermal band information be incorporated into studies which currently use only data from the reflective bands?

This research concluded:

- The thermal band is a valuable data source by itself, unlike most of the reflected bands, which are useful only when used in combination. From the thermal band data it is possible to derive surface temperatures and, hence, can be useful in micro-meteorological studies, especially in more remote areas.
- The thermal band information can also be used as a verification tool.
- Discriminant analysis revealed that band 6 data contains considerable information for the discrimination of land cover classes in the dry tropical forest ecosystem of Yucatan, Mexico.
- For the best results in remote sensing analyses of land cover change multiple data sources should be used creating both continuous and discrete information relating to the land cover processes. In order to achieve a comprehensive description of surface processes these indicators must be used together, and band 6 data must be incorporated.

Overall significance of this research

> *The accelerating changes to the Earth's environment are being driven by growth in the human population, by the increasing level of resource consumption by human societies, and by changes in technology and socio-political organizations. Four aspects of large-scale environmental perturbations are considered here [GCTE research foci] under the term "global change": (i) changes in land use and land cover; (ii) the world-wide decline in biodiversity; (iii) changes in atmospheric composition, especially to increase CO_2 concentration; and (iv) changes in climate.* (Walker and Steffen, 1997).

Of these four themes, two have been addressed in this research. Realistically as the human population continues to expand the most important component of global change in the near future (10-20 years) will relate to land use and land cover change. Most of this change will occur in developing countries and hence, the importance of improved monitoring techniques (Chapter 6) and continuous analysis of location specific studies, especially those located in developing countries (Chapter 5), are essential. Over a longer time-frame (> 20 years) climate change is the major issue to be addressed, as is discussed here both for forested (Chapter 4) and agricultural (Chapters 2 and 3) ecosystems. Given the certainty of atmospheric CO_2 increase and the resultant change in climate which is already occurring (IPCC, 2000) such research as that presented here is essential in order to provide knowledge of the systems response to change and hence to allow for potential adaptations. In addition, climate change will impact other aspects of our global environment, beyond the direct effects relating to changes in temperature, precipitation, etc., and will be a major factor in political processes, regional planning, and resource management decisions (Walker and Steffen, 1997). In order to adapt to changes in future climate, both in terms of negating the worst impacts and capitalizing on any opportunities that arise, the decisions must be based upon sound scientific understanding of terrestrial ecosystems, their change processes and patterns, and their interactions with global change. This research attempts to start to lay a foundation in these issues for the midwestern U.S. in terms of ecosystem response of both forests and agricultural systems to climate change, and to improve the monitoring and explanation of land cover change processes across three developing country regions (Honduras, Guatemala, and Mexico). As such this research is considered a contribution to the current global change arena.

Policy Implications for the Midwestern United States

The research undertaken here has specific implications for policy within the Midwestern United States. More specifically there may be price support or incentives given to farmers to grow certain crops, soil management may be come of increasing importance, genetically modified foods may become more of a necessity and for forestry there are also some major implications, especially relating to biodiversity.

Under different scenarios of future climate change yields of maize decrease compared to current values, for most southern regions of the states and also for all areas under more extreme climate scenarios. This may have some major policy implications for the study region. In addition to maize yields doing poorly the crops soybean and wheat do increasingly well under these same conditions. In part this is due to the C_3 versus C_4 crops, with C_3 crops having a fertilization effect of around 20% due to increased levels of CO_2 in the atmosphere. Most current weeds are also C_3 plants and so will also grow better under future climate scenarios. However, maize, a C_4 crop, will have problems due to weeds outcompeting it, especially in its earlier growth stages, and hence an increased need for herbicides. A potential incentive to move farmers away from maize may include increased taxation of herbicides. In addition, shifts from price supports for maize to price supports for soybeans (or wheat) are potentially plausible in the future. Soybean is a better alternative due to the much higher yields (increases of 100% in yield at some locations modeled), and also due to it being able to replace maize in many of its current uses: oils etc., as well as a foodstuff. Hence, policy could either tax maize or give price supports or other incentives for farmers to grow soybeans (or wheat). Current incentives are set up for maize, which would be ended and these price supports given to other crops would make many farmers switch. As the Soil Conservation Service (SCS) currently tells farmers what to plant, when to plant, and how much to plant, an easier way to change crops grown, may be to mandate local SCSs to better manage their farms and to plant less maize due to their lower yields and more soybeans, wheat, or other crops. If the SCS is involved the farmers may feel less like the government is involved and more like this is a local issue, hence, they would be more likely to adapt and to do so with less resentment.

In addition to having price supports switch however, there would need to be accommodations made to a number of other sectors if a switch from maize to soybeans (or other crops) were likely. Specifically, there would need to be some incentives or aid to manufacturing companies to develop techniques, and to promote demand, for soy based products. Soybeans can be a substitute for most maize products but a switch from maize to soybeans would need a major cash flow to get going. In addition, for many of the Midwestern states, and specifically for Indiana, maize is grown predominantly for use as animal feed and so the animal husbandry industry would also undergo some significant changes should maize production decrease. Such changes would results in the industry needing to find alternative animal feed crops, which should be viable given how soybeans and wheat increase in yields, but this will also take incentives for these industries to look to alternatives, and money to make such a switch.

For forestry, future changes in climate may mean a shift from the current forest mixes of beech-maple and oak-hickory to a forest system dominated more by oak-hickory. In terms of forestry this will please many forest managers to whom oak and hickory are more valuable timber trees. However, such a shift, especially if it occurs quite quickly, and due to the significant barriers to movement (large agricultural areas limit species movement) could have dramatic impacts on biodiversity. Foresters will not try to conserve beech and maple trees as these are not commercially viable but these species are important for conservation of biodiversity. Hence, if these species are lost under changed climate scenarios, and northward movement is limited or constrained due to current land use then widespread loss of species is inevitable. Federal legislation would likely be needed to prevent this occurrence. One possible solution would be to revise the endangered species act to allow for government intervention to preserve potential forest lands which are not currently considered “critical habitat”.

As climate continues to change many more potential issues will arise that were not included in the models e.g., pests, pathogens and disease, but which may have some significant policy implications. The discussion here has simply attempted to highlight some of the potential policy implications of currently modeled changes in the agricultural and forest ecosystems and is by no means an exhaustive list. As the models of change improve so to will our grasp on some of the potential implications for society and also some possible remedies or incentives for change which may become plausible.

Opportunities for future research.

This research allows me to build both on the methods and the results in my future research and to continue along these research avenues. Future research will incorporate both climate change and land cover change analyses more explicitly with changes in land cover being linked to climate change and be used to analyze such changes spatially and temporally.

The research discussed here in Chapters Two and Three is part of a larger project examining possible farm-level adaptations to the potential changes predicted from the crop modeling. Continuing research will incorporate crop modeling of soybeans (DSSAT SOYGRO) and wheat (DSSAT CERES-wheat), both in terms of the potential mean changes in future climate and the potential changes in climate variability. A manuscript on the soybean results has been sent out for review to the journal '*Climatic Change*' and also a number of book chapters are being written for the book due out in 2001 through Kluwer Publishing. These results will be used as inputs into the Purdue Crop Livestock Program (PC/LP) model for farm level decision analysis. The results from the DSSAT models (CERES-maize, CERES-wheat, and SOYGRO) flow into PC/LP, then as management/economic decisions change the type of production, results are fed back into the crop model for further adjustment to crop production modeling. This will allow the development of farm level strategies to be created and then tested by running back through the model scenarios with the adaptations incorporated. Additional funding is also being sought in order to expand upon the results given here and to incorporate more climate scenarios and potential for adaptations into this research area.

Chapter Five discussed research in Honduras and Guatemala. This work is still continuing and will include more comparison work across these sites in the future. Two research papers have been written. The first, based more on the methods employed is currently under review by the journal '*Field Methods*'. The second has recently been submitted to '*Mountain Research and Development*' and includes more detailed forest plot and GIS analysis. A 1991 Landsat TM image has been ordered and will provide an intermediate date for analysis in land cover change. In addition a 2000 image is being sought for March 2000 to coincide with the fieldwork done earlier this year. This ongoing research aims to address the following issues: (1) investigation and description of forest change areas, as identified from time series analysis, of the La Campa area, (2) testing of hypotheses concerning the factors for forest change and conservation, and (3) testing and refinement of the methodology for general application and comparative analyses of CIPEC sites.

More broadly, the case of La Campa raises questions relevant to the investigation of forest change at different scales of analysis. In particular, what are the major factors influencing forest change at the local (micro-) level, and do these differ at the meso- and macro-levels? This question has implications relating to understanding the role of human decision-making in forest environments (made most directly by forest users), the linkages and contradictions between levels of analysis, and the analysis of policy impacts. We can also ask whether La Campa is a unique case, or whether it may be one of many areas in which local circumstances and institutions lead to forest conservation or restoration. If the latter is true, then the results have important implications for policy-making, which tends to be based upon aggregate data and may therefore make incorrect assumptions about the policy incentives and sanctions needed for better forest management. Of particular concern is the potential for national-level policies to erode or prohibit local institutional arrangements that protect forest resources. The results of this study will provide the potential to identify other areas with similar patterns, to learn more about the frequency of reforestation in the TM footprint for the western Honduras/eastern Guatemala region, as well as for other CIPEC locations, and to link with other research groups in these areas (e.g., Edwin Castellanos in Guatemala).

I will use all of the methods discussed in this research portfolio in my future research. In addition the research areas of Western Honduras-Eastern Guatemala and the Midwestern section of the United States will continue to be the focus areas of my research. Over time the global change theme will become more unifying as we are better able to monitor vegetation change processes and link these to natural and anthropogenic climate change, then these will also become better linked within my research. This is the ultimate direction and goal of my research efforts at this time, within the global change framework of analysis.

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JANE SOUTHWORTH

Doctoral Candidate
School of Public and Environmental Affairs (SPEA)
1315 E. Tenth Street
Indiana University
Bloomington, Indiana 47405-7547

Telephone: (812) 855-4953 Fax: (812) 855-7547 jsouthwo@indiana.edu

EDUCATION

2000	Ph.D.	Environmental Science	Indiana University
1996	MA	Meteorology and Climatology	Indiana University
1992	BSc.	Physical Geography	Leicester University, U.K.

RELEVANT EXPERIENCE

1997-2000:	Graduate Research Assistant in Remote Sensing and GIS analysis at CIPEC (Center for the Study of Institutions, Population, and Environmental Change), and in Climate Change Modeling of Crops and Forest Ecosystems at the Midwestern Regional Center for Global Environmental Change (NIGEC), Indiana University, Bloomington, Indiana.
1996-1997:	Lab Instructor for Global Environmental Change (E105), Environmental Remote Sensing (G335) and for Remote Sensing of Global Change: Human and Ecological Dimensions of Land-use and Deforestation (G540).
1996:	Masters Thesis: The controls on stomatal conductances within the Los Angeles Metropolitan Area.
1993-1996:	Independent Course Instructor for Weather and Climate (G109), Introduction to Physical Geography (G107), and Introduction to Human Geography (G110).
1992/1994:	Summer Research Assistant for the Chicago Urban Forest Climate Project.
1993:	Summer Research Assistant for the Los Angeles Metropolitan Area Urban Climate and Vegetation Project.

RESEARCH INTERESTS

Effects of global climate change and changing climate variability on agricultural processes and forest ecosystems. Modeling future scenarios for 2050-2059 based on climate data from the Hadley Center Model (HADCM2), with a number of different climate runs, for midwestern agriculture. Remote sensing of land use land cover change, and the differentiation of biophysical and human influences on the causes for change, using remote sensing and GIS techniques. In addition, the use of the thermal band data (Landsat TM band 6) as a tool in land cover analyses and as an independent data source for vegetation and climate studies.

PROFESSIONAL SOCIETIES

American Geophysical Union
American Meteorological Society
American Society for Photogrammetry and Remote Sensing
Association of American Geographers
Ecological Society of America

AWARDS AND HONORS

1999-2000 Founding member of the School of Public and Environmental Affairs PhD Students Executive Committee (ASPS)
1998-2000 Founder and President of the British Student Association at Indiana University
1997-2000 Graduate Student Representative for Ph.D. students in Environmental Science in SPEA
1997-2000 International Center panel committee member
1996/1995/1994 Chairman Graduate Student Recognition Award: Outstanding Academic Performance.
1995 Graduate Student Fellowship Award.
1994 Steven S.Visher Award in Recognition of Outstanding Research in the field of Climatology.
1991-2 Vice-President of the Geography Association, Leicester University, England.

SELECTED PUBLICATIONS AND PRESENTATIONS

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