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Adaptive Analysis of Locally Complex Systems in a Globally Complex World

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WWF

ABSTRACT

Zambezi Valley agro-ecosystems are environmentally, economically, and institutionally variable. This variability means that it is not possible to measure everything necessary to develop a predictive understanding of them. In particular, because people and their environments are constantly changing, what was measured yesterday may change by tomorrow.

Here, I describe elements of the approach that I have developed to address this problem. Called DAAWN, for Detail as and When Needed, the approach advocates an iterative and multiscaled methodology in which we first capture as broad an understanding of the system as possible and then use awareness developed at this scale to identify where to focus subsequent, more detailed, investigations. Because we cannot hope to measure or monitor everything in these complex and adaptive agro-ecosystems, the approach requires us to make judicious use of all available knowledge about the agro-ecosystem. The DAAWN approach is rooted in systems theory, but is tempered by systems and problems where boundaries are not clearly defined, where nonlinearities are the norm, and where structural and functional change is the order of the day.

I describe a few of the most important data collection tools and methods that were developed to record the knowledge of local people and to observe, monitor, and measure changes in their resources. Of particular importance is the tool that I call a "spidergram." This tool, which I used extensively with village informants, symbolizes the DAAWN approach and was a major stimulus for its development. Simulation models provide another very important tool; here, I offer some examples of spatially explicit, multi-agent models. Some key findings of the research on Zambezi Valley agro-ecosystems are also briefly presented.

KEY WORDS: comples adaptive systems, household and resource economics, livelihood strategies, modeling, multi-agent simulation models, natural resource use, participatory systems analysis, southern Africa, spidergrams.

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IMAGES FROM A CHANGING WORLD

Three hours north of Harare, Zimbabwe's capital city, the majestic view of the Zambezi Valley, lying some 1000 m below the highland plateau, is breathtaking. There are those who believe that this is the last wilderness in Zimbabwe. Some of the largest concentrations of wildlife in southern Africa occur in the valley. It is also the last land frontier for peasant settlers hoping to carve an agricultural future for themselves. To the government, it is both a means of earning vital tourist dollars and a way of postponing, for perhaps another decade or two, the pain of dealing with population growth and burgeoning poverty.

To descend into this wilderness is to enter a dimension of Africa that is rapidly vanishing. There is no electricity and virtually no telephones. There is no CNN, and local television broadcasts are only now starting to descend via cheap receivers attached to old car batteries. When dry, the roads are dusty and corrugated. When wet, they are virtually impassable. There are no large towns, just a few small business centers, each with a few tiny grocery stores that sell everything from matches and sugar to bicycle parts and ox-drawn ploughs. For most of its inhabitants, access to the highland plateau is via unreliable services provided by noisy, slow, and immensely uncomfortable buses, by bicycle, or by foot.

Understandably, most people living in the valley are all too glad that "wild" Africa is disappearing. Having lived with the realities of remote village life for decades, they find little glamour in having to walk for a day to the nearest clinic to be treated for yet another bout of malaria. Nor is there much excitement in having to stay awake all night banging tins and drums to drive elephants away from next year's food supply. Local people dream of development--a future with good roads, good schools, good hospitals--one in which they do not face starvation with each successive drought. They dream of a future when they can live in houses made from bricks and mortar and when their children will not be as poor as they have been.

Since the beginning of this century, the people of the Zambezi Valley have been packed up and moved around with little more consultation than is given to checkers on a board game. The colonial government moved people to make way for Kariba Dam, for national game reserves, and for settlers. In the latter half of the 1970s, during the war of liberation, the Rhodesian government forcibly moved people into encampments, called protected villages, wherein their movements and activities were stringently curtailed.

Following the anguish of the war years, in which the Zambezi Valley was a major front, people of the valley might have been justified in hoping that their dreams of development and self-actualization would come true. Sadly, little has changed. In the mid-1980s, the Zimbabwe government embarked on a new round of moving people, this time in the name of development or resettlement. Even now, in the late 1990s, some of the same people who were moved in the 1980s are to be moved again, this time to make way for a new irrigation scheme!

Although people have lived in the Zambezi Valley for centuries, their rights to the land and resources are, in many instances, still far from clear and even farther from being secure. The land was, and still is, held in trust for them by the President of Zimbabwe. Up until the mid-1980s, all wildlife was owned by the State; now the Rural and District Councils own it. Legislation forbids people to cultivate within 30 m of rivers or in wetland areas, both traditionally important areas of cultivation. Several plant and tree species are protected and their use is prohibited. Until very recently, the government strictly controlled markets for grain, cotton, and livestock. In some areas, people are not allowed to keep cattle; in other areas, the number of cattle they may keep is restricted. The ability and willingness of successive government authorities to monitor and enforce these rights have varied from place to place and from time to time, seldom clear and seldom certain.

Uncertainty and variability: the essence of Zambezi Valley agro-ecosystems. *Uncertainty and variability:* climate, politics, prices, livestock populations, malaria outbreaks, soils, central government policies and actions, bus services, health care, food supplies, input supplies, insect pest outbreaks, crop yields, livestock diseases, and the location and movement of elephant and buffalo herds. *Uncertainty and variability:* nothing new to these agro-ecosystems; people have been adapting and coping with high levels of variability and uncertainty for centuries. They have developed strategies that comprise multiple enterprise options, from a host of crop and livestock production activities to trade, craft, natural resource harvesting, and employment in other parts of the country. The relative contributions of these strategies to individual, household, and community well-being is constantly adjusted to prevailing conditions and expectations. Crop production has been the mainstay of these systems for centuries, but when there is a drought or series of droughts, people shift to other means of satisfying their basic needs.

The economies of southern Africa are inextricably linked to the rains. At the macro scale, when the rains are plentiful, economies expand and boom; when the rains fail, the economies contract and suffocate. When the rains fail, as they so often do, agricultural growth stagnates and people stream out of the Communal Areas (CAs) to look for work, try their hand at trade, at gold panning, at anything that will help them to get through until the next rains. When the rains return, people stream back to their homes to plant, tend herds, and farm again. These people and the systems that they have developed are well adapted to uncertainty and to variability: those who could not or would not adapt, or who made the wrong choice at some critical juncture, have gone.

Yet, the world is changing at breakneck speed. Prices of goods and services that people of the Zambezi Valley own or produce are now determined on the floors of international stock exchanges or at international meetings like the Conference on International Trade in Endangered Species (CITES). Massive population growth rates are stressing public services, with little hope that the formal economy can absorb the growth in the labor pool. AIDS hovers in the background like the Grim Reaper, waiting to take its toll on the young, the old, the innocent, and the economy! Zimbabwe is a young nation: the constitution and the legal and political systems are like newly tailored clothes that do not yet fit. They need adjustment to fit comfortably. Old sources of uncertainty and variability make way for the new.

Within this changing environment, people of the Zambezi Valley seek to satisfy changing needs with changing technologies, which they use in conjunction with changing resources. Along with television, movies, the apostolic church, and advertising, the Coca-Cola culture has arrived. Young people are challenging the traditional rights of long-dead ancestors and parents to approve wives, careers, and leaders. Immigrants from the overpopulated parts of the country flood to this last frontier, bringing new methods and ideas. They also bring new political affiliations, aspirations, and conflicts. Will the agro-ecosystems of the Zambezi Valley adapt and continue to survive? Will their inherent resilience accommodate these new sources of variation and uncertainty? What will they become and which characteristics will they retain or lose altogether?

AN OVERVIEW

My research on Zambezi Valley agro-ecosystems formally started in late 1991, when I began my doctoral field research. Naively undaunted by the enormity of the questions for which I sought answers, I was introduced to the people of Masoka village. At a meeting of community members, I explained what I hoped to achieve in my research and asked their permission to conduct the research in Masoka. Their approval propelled me on an investigative journey that was to profoundly alter the way I conceive of agro-ecosystems and the process of scientific inquiry. This essay is the story of my attempts to find patterns in the structure and functioning of agro-ecosystems of Masoka, Gonono, Gutsa, Negande, and Sinansengwe (Fig. 1) that we could then apply to the hundreds of other agro-ecosystems in the Zambezi Valley. In looking for patterns, the seeds of theory, I developed an approach paraphrased by the acronym DAAWN: Detail As And When Needed, which is an underlying theme throughout the essay. I start by explaining why it is essential to understand these agro-ecosystems and why it is so difficult to do so reliably. Thereafter, I interweave methods, data collection tools, and analysis with my use and perceptions of local, observational, and scientific knowledge applications. Designing and building computer simulation models are also large components of the approach that I have developed and used, and I include them as well. I then describe current images of adaptive systems and the evolutionary process that I have followed. Finally, I look to the future and routes I expect to explore to enhance my understanding of agro-ecosystems and how to study them.

Fig. 1. Map showing the five Zambezi Valley study sites in relation to major urban centers in Zimbabwe.

GIF image file (32 K)

IMPORTANCE AND DIFFICULTY OF PREDICTING THE FUTURE AGRO-ECOSYSTEMS

Masoka is a small but remarkable community thrust into the forefront of development thinking and practice through their CAMPFIRE project. CAMPFIRE, an acronym for Communal Areas Management Program For Indigenous REsources, was an exciting Zimbabwean initiative that sought to give control of wildlife and other natural resources to local people. Predicated on the expectation that people who bear the costs of living with wildlife should reap the benefits, CAMPFIRE provided communities with direct, visible monetary evidence of the value of natural resource capital. CAMPFIRE proponents hoped that, with local institutions controlling resource use and strong price cues signalling values, wildlife would be a sustainable land use option for many of these often agriculturally marginal communities.

Conservationists suddenly had a powerful new paradigmfor fostering natural resource conservation. Development advocates had an equally powerful tool for enhancing the well-being of people in the Zambezi Valley. For once, these two groups, so often at loggerheads, were working in tandem to achieve a common vision: community development through sustainable use of natural resources. As if with the wave of a wand, the relationship between human communities and wildlife was redefined. Once considered to be poachers, local residents were now responsible managers of increasingly valuable resources. In recent years, cash payments (dividends) to households were the equivalent of >90% of average annual household cash income! Residents also built their own primary school and clinic from wildlife-generated revenues. Imagine: for decades, local residents had been perceived and treated as little more than environmental pillagers. Suddenly, their status was elevated to that of caring and responsible natural resource managers. Such transformation!

Despite the euphoria and excitement of seeing local communities emerge economically and environmentally, responsible and effective management institutions do not evolve overnight. As a researcher, I needed to be cautious in my optimism. Dr. David Cumming, leader of the World Wildlife Fund (WWF) Project Office in Zimbabwe, shared this caution, for good reason. So many famed development projects lay awash in dusty basins of rust, corruption, insensitivity, or outright failure. Would CAMPFIRE end up the same way, great promise and hope turning to dust in the harsh African reality? Would we know 10-15 years down the road, or were there indicators of success or failure that we could identify before failure was irreversible? Was it possible, we asked, to be proactive and develop an understanding of agro-ecosystems that would enable us to confidently predict future states or behaviors? Could we use that understanding to identify policies, management actions, or agro-ecosystem designs that would enable people to continuously satisfy their needs and perhaps even improve their well-being? Would ecosystem well-being be maintained or would this unique valley landscape, with its untapped potential, be reconstructed as cotton fields to compete with the millions of other cotton fields around the globe? The view of CAMPFIRE-type projects as a resounding success is not universally accepted. Indeed, Christopher Barrett and Peter Arcese (1995) present evidence questioning the success of these initatives.

Our caution was not a hankering to return to the view of villagers as environmental pillagers. Far from it! Dr. Cumming was one of the original architects of the CAMPFIRE vision. However, history all too often repeats itself. We hoped for a different script for this part of Africa, in which both the people and the environment lived happily ever after!

Why is it so difficult to predict the future behavior or structure of an agro-ecosystem? There are multitudes of good reasons, but the major ones are fairly straightforward. Zambezi Valley agro-ecosystems are variable and keep on changing. With limited resources at our disposal, it is impossible to know everything about an agro-ecosystem. There is neither theory nor procedure to guide us in choosing which components of the agro-ecosystem are critical in determining its future structure or function.

Economists observe economic problems and seek economic solutions; agronomists observe agronomic problems and seek agronomic answers. Given the scant success that solutions based on academic disciplines or ideological persuasion have had in alleviating poverty or environmental degradation, it behooves us to seek a more holistic awareness of Zambezi Valley agro-ecosystems, and to use this knowledge to seek problems and solutions. Yet, if we cannot observe or measure everything and most things are continuously changing anyway, how do we develop this holistic understanding?

We must do the best we can with what is available. I have found a smattering of theory, which may or may not be relevant to these agro-ecosystems, and a considerable body of knowledge distributed among a large number of people and organizations. Unfortunately, not only is this knowledge widely distributed among a range of different "custodians," but also it is often coded, recorded, or represented in different ways by different custodial groups. Physical, biological, and social scientists commonly use numeric coding and storage methods. Although anthropologists and historians commonly use qualitative descriptions, local managers and people use myths, stories, rules, and shared experience.

Classical science rejects knowledge that has not been acquired through repeatable measurement or observation. Cumulative experiences of the thousands of people living in the Zambezi Valley for the past several centuries form the greatest source of knowledge available. Classical science would have us reject this wealth of knowledge and admit to almost complete ignorance, for scientists have done little observation or measurement in Zambezi Valley agro-ecosystems. More disturbing still, at the rate at which scientists are measuring in the Zambezi Valley, we will be ignorant for a long time to come and, in many cases, will never know what we did not know!

To address the very pressing problem of understanding Zambezi Valley agro-ecosystems, we must use all available knowledge. Who knows better the needs and objectives of local people than local people themselves? But they do not know everything and some of their knowledge is incorrect, just as some scientific knowledge is incorrect. We need a means of capturing knowledge from these widely disparate sources and then integrating it, with relevant theory when appropriate, to yield a coherent understanding that can be easily manipulated to identify areas requiring the most attention or greatest effort. In the next section, I describe some approaches that I have used to capture knowledge, translate it into common codes or symbols, and integrate it into a coherent whole using computer simulation models. Many of the methods that I have developed build on the pioneering work of Robert Chambers (Chambers 1983) and others who successfully demonstrated the importance and validity of local knowledge and values.

THE RESEARCH WEB WE SPUN

Of the many different sources of knowledge that I have used in analyzing Zambezi Valley agro-ecosystems, three stand out as most important: (1) knowledge that local people provide; (2) knowledge gained through observations of people's activities; and (3) knowledge gained through scientific measurement. I will now describe some approaches and tools that I developed and used to capture knowledge from each of these three sources. They are certainly not the only tools that I have used; let me illustrate.

Insight and knowledge of Zambezi Valley agro-ecosystems have been gained in a variety of unique ways. I have had community members write and illustrate their own environmental histories, just now published as books for use in their schools. I have had a community leader map sacred sites in the eastern Valley. I was successful in encouraging young school children to write essays, for a competition, about their household's use of natural resources. I have organized and run workshops with scientists and government extension agents. I have scoured various sources of secondary data and I have spoken to people who work in a wide range of disciplines.

Local knowledge

In Masoka (and in each subsequent site that I have studied), I began my research by asking the community, at a public meeting, to elect 6-10 people to represent the community's interests and knowledge during the research process. I insisted that at least half of the elected group be women; other than that, I lay down no specific conditions. I did ask that the range of skills, knowledge, and interests in the community be represented. I asked for some older people to reflect traditional culture and aspirations. I asked for young people to represent the future. I asked for representatives from wealthy and poor households. I asked that some members be educated and some not. I did not insist on these criteria: I presented them as guidelines. I called these small group members Village Representatives (VRs). They played a key role in data or "knowledge" collection. I worked with them intensively in workshops of 4-10 days at a time, over a period of up to two years. With each of these groups, I explored the most intimate and the broadest aspects of community life.

"Spidergrams" were a major, vital tool in these explorations (Fig. 2). I developed and used them to focus my questions. In each site, I began a single spidergram by asking what households needed in order to live an adequate life in their community (Table 1). I would get the Village Representative (VR) group to draw a circle on the ground to represent that question. As they started generating parts of the answer to that question, I would ask the group member who provided the answer to draw a line radiating out from the circle. A symbol (often stones or other objects, but sometimes words) was placed at the end of the line to represent that component of the answer. For example, the group might mention land, water, housing, leadership, food, clothing, and cash. A separate line radiating from the central circle and a symbol would represent each one. The group would discuss each answer for each component and agree that these were indeed the essential things that a household needed in order to lead an adequate life.

Fig. 2. An example of a spidergram showing two levels. The scoring at the first level is open-ended, whereas the scoring in the second level (i.e., land) is constrained.

GIF image file (19 K)

Table 1. The 10 most important factors required for an adequate life in each Zambezi Valley agro-ecosystem, identified by Village Representatives using spidergrams. Numbers in parentheses are factor importance rankings.

Gonono	Gutsa	Masoka	Negande	Sinansengwe
Food (1)	Land (1)	Land (1)	Store-purchased food (1)	Health (1)
Water (2)	Water (1)	Water (2)	Health (1)	Knowledge (2)
Fields (3)	Homestead (3)	Food (3)	Land (1)	Fields (3)
Draft (4)	Cash (4)	Cash (4)	Rain (1)	Land (4)
Equipment (4)	Food (5)	Community (5)	Cash (5)	Livestock (5)
Market (6)	Livestock (5)	Homestead (6)	Water (6)	Utensils (6)
Blankets (7)	Education (7)	Equipment (7)	Knowledge (7)	Farm tools (7)
Clothing (7)	Equipment (8)	Education (8)	Livestock (8)	Cash (8)
Household utensils (9)	Transport (8)	Non-food grocery (9)	Clothes (9)	Community, culture (8)
Leadership (10)	Employment (8)	Capital (10)	Education (10)	Water (8)

Once group members reached consensus on the components of an answer, I asked them to identify which of these was least important to the well-being of households. The VRs would discuss this among themselves and agree on one of the identified components. For illustrative purposes, assume that they chose "leadership" as the least important component. The group would then place a single stick or stone on the line or symbol representing leadership. I then asked them to go to each component they had identified and score that component in relation to the least important component (i.e., that which they had given a single point). A component with five points was perceived to be five times as important as the component with one point, and so on. Each time, the group would reach consensus on the allocation of points.

The first spidergram level was complete when the group had scored each component of the answer. I would then select the first-level component with the highest score. This became the center of a new question at the second level. I could ask several types of questions at this second level. Let us suppose that the VR group had given land the highest number of points. The next question might be "What types of land are found in Masoka?" Or I might ask, "What does a household need to do in order to get land here in Masoka?" As before, they drew the components of their answer as lines radiating out from the land symbol. When all components were identified, I again asked the group to score each component to reflect importance. I could use one of two different scoring methods. In the first method, called the open-ended scoring method, no limit was placed on the number of counters or points that could be used. This method was useful for identifying relative importance or preference and was especially important when components were valued quite differently. I called the second method a constrained scoring method, which allowed only five counters per component or "spider leg" of an answer. There was no significance to the number five other than convenience: too many points were unmanageable, too few had little resolution. This latter approach was most useful when the factors or components being scored were part of a whole, such a budget allocation or a land allocation.

After dealing with the most important component of the first spidergram level, the group would go to the second most important component, then the third most important, and so on until the major components were complete. Thus, the focus of the investigation was driven by what was perceived as meaningful to the VRs. The process of asking the question, identifying the components, and then weighting their importance, preference, size, or value was repeated for each component that was considered significant enough, relative to all the others.

The spidergram provided a tool with which I could explore knowledge, understanding, values, and expectations. I could expand a spidergam almost without end by treating each radiating leg as the node starting a new question, i.e., a new spider. Most importantly, it enabled me to focus on what people knew or thought to be most essential. Where components had low scores, I might not expand further. Where components had high weights, I might expand to five or more levels. The situation determined the degree of detail and the boundaries of the analysis!

A WEB WOVEN

Working with Village Representative groups provided an illuminating window into nearly every aspect of the lives of the Zambezi Valley people. By working closely with the same groups over extended periods, I developed a trusting relationship in which Village Representatives felt comfortable in expressing great detail about their communities in ways approaching the detail of an anthropological investigation. Unfortunately, "truth" can be quite subjective. Local knowledge is as error prone as any other knowledge source. Perception and perceptual error have two significant aspects that need to be confronted in agro-ecosystem (or other social) analyses. The first is the need to identify what is true, in the sense of a repeatable scientific experiment. If someone else were to carry out the activities under the same conditions being investigated, would they achieve the same result? The second aspect is that if people make decisions and act on a perception, even if it is incorrect, then that perception is an important motivator and needs to be acknowledged and dealt with appropriately.

To identify errors in the knowledge or perceptions of the Village Representative groups, I used an approach called triangulation. The concept comes from using three or more points to find out where you are in finding your way. This is an attempt to identify the same knowledge, either from several different perspectives or using different methods. If the different perspectives or different methods all yield the same result, then the degree of confidence or belief in the results improves. If some methods produce different results, then our confidence in the results may be shaken and further investigation may be needed to establish whether there is notable error in the perception or belief.

Triangulation is a powerful tool that apparently is used all too infrequently in investigations involving people's perceptions, belief systems, knowledge, or understanding. Most investigations of agro-ecosystems that seek to understand people and their actions make use of questionnaires. Although they may occur more frequently, I have seen only one case in which researchers returned to validate the findings of a questionnaire survey. In general, once a survey is completed, that is it; information is entered into some database, results are analyzed, and the report or paper is written. My own work has not been immune to such actions. In each of our studies, we used a questionnaire to obtain information on demographics, household resources, household activities, and perceptions. In all of these surveys, we asked people how many acres they planted, in the past season, of each of several crops. We also asked what their total yields were. These data were duly entered into our growing database; they were checked and then analyzed.

In this study, however, I returned and worked with Village Representatives, asking them similar questions, but in a different way. In one site, I discovered that neither the VRs nor most other people in the community had any idea what size an acre was, and yet I had several hundred questionnaires from this community with information on the number of acres of each crop planted in the last season!

Surprise! Surprise!

Observational knowledge

Observations of people's activities proved to be an especially meaningful method of capturing knowledge about their preferences for goods and services and what they were willing to pay for them. Private property rights did not govern the allocation or use of most of the resources available to households, nor were most of these resources traded in markets. Thus, establishing their value was exceedingly difficult. One currency was, however, common to all transactions involving these resources: labor time. I used labor time and local wage rates as a conservative indicator of the value of all goods and services passing through the local economy. This enabled me to estimate the size of the total economy of households and the relative contributions of various sectors to this economy (Table 2).

Table 2. The percentage of total labor time, weighted by the wage rates for each activity, allocated to each sector of household economies in five Zambezi Valley agro-ecosystems.

	Gonono	Gutsa	Masoka	Negande	Sinansengwe
Animals	15	31	<1	51	63
Fields	52	23	49	22	14
Natural resources	22	28	25	16	14
Home	12	15	25	10	9
Gardens	<1	3	<1	1	<1
Total	100	100	100	100	100
Total value of labor (Zambezi $ per household per year)	567	1321	429	417	295

We clearly could not follow households through their development cycle to test our understanding of the processes of household decisions and resource use, so I devised a sampling strategy using longitudinal data as a proxy for a time series. It was not perfect, but the best we would get. Based on the age of the household head, households were grouped into five classes. A sixth class of female-headed households was added: they constitute a large proportion of Communal Area households, but their access to land, credit, information, and labor is quite different than that of men. They face a different set of problems.

Two wealthy and two poor households were then randomly selected in each development stage class in each of five sites across the Zambezi Valley. Sites were selected to represent corners on a two-dimensional axis of agricultural production potential (high and low) and population density (high and low). Wherever possible, enumerators were employed from within each selected household to record household activities every week over a 9-12 mo period. Almost everything imaginable was monitored. Consistent with the spidergram approach of investigating in greatest detail the most important components of a system, I devised an adaptive data collection instrument (Fig. 3). All activities were monitored every week at a coarse level on "mother sheets:" yes they occurred, or no they did not. For important components, much greater detail on who, what, when, and how much was collected on "child sheets." This data collection tool enabled us to track everything at a very coarse level and key things in great detail. Rather like modern object-orientated computer programs, data collection was activity driven. Only when activities happened on the ground was data collection initiated for that type of activity.

Fig. 3. Example of data collection structures for household monitoring: maps linked to "mother" and "child" sheets.

JPEG image file

In the case of fields and common-pool resources, enumerators also mapped where activities had occurred. For field activities, these were sketch maps of each field. Each week, enumerators would overlay the original sketch maps with tracing paper, drawing onto the tracing paper where activities had occurred. Each activity drawn on the map was given an identifying code relating it to the specific mother sheet and entries in the appropriate child sheets. With common-pool resources, we needed more detail, so we trained enumerators to use simplified maps of their agro-ecosystems. Weekly, they marked on these maps where each activity occurred, using a code corresponding to the code on the mother sheet and the child sheets for that activity.

Data from the mother and child sheets were entered into an attribute database. Data on the maps were digitized for use in our GIS. By linking the attribute database to the GIS maps via identifying codes, we were able to investigate spatial patterns of resource use and to calculate the "catchment" areas from which households were using their common-pool resources (Table 3). We also discredited one of the key assumptions of CAMPFIRE, which was that local institutions (village and ward boundaries) would control use of natural resources (Fig. 4). We found this to be less true than previously thought. We identified which resources were under most pressure from human use. The importance of rivers to these semiarid agro-ecosystems was clearly highlighted and has stimulated further research to understand the significance that rivers play in Zambezi Valley agro-ecosystems (Fig. 5).

Table 3. The areas from which households harvested or used natural resources ranged from about 6 km^2 to 17 km^2. The harvest catchment areas for different households overlapped.

	Mean area (km^2 per household)	Coefficient of variation (%)
Gonono	12	17
Gutsa	17	18
Masoka	6	23
Negande	9	21
Sinansengwe	11	22
Overall average	11	23

Fig. 4. All households collected or used natural resources within their own village areas. Over 85% of households used resources from villages other than their own, and 20% of households used resources from wards other than their own.

JPEG image file

Fig. 5. Using information recorded by enumerators on maps and on "mother" and "child" sheets, we were able to examine how Zambezi Valley agro-ecosystem residents used their landscape. This figure illustrates the importance of rivers in the economies of these agro-ecosystems.

GIF image file (16 K)

Scientific knowledge

I found that, although local knowledge was excellent at describing and classifying resources, activities, or observable events, little was known about agro-ecosystem structures or states that could not be seen or felt. Similarly, knowledge of local people about processes that lead to a change in state of various components of their agro-ecosystems was often weak. Local knowledge was inadequate for understanding many of the key processes in Zambezi Valley agro-ecosystems and for many of the very fine- or large-scale details. Consequently, I had to use more formal scientific observations and measurements. Although the scientific method offers a powerful suite of tools for collection and analysis of information, it also operates within a straitjacket of its own making. I have already discussed science's denial of knowledge other than its own. Formal science, as traditionally practiced, is exceedingly powerful in relating cause and effect in simple and unambiguous situations. Science has been much less successful when faced with complex problems for which it has few tried and tested methods. The rigor and success of much modern science is due largely to the transformation of complex problems into simple models of cause and effect. Unfortunately, few of the problems that I have faced in the analysis of Zambezi Valley agro-ecosystems are well behaved. Cause and effect are seldom linear and seldom can they be irrefutably linked. Normal distributions seem like a Holy Grail that other people talk about but rarely see. Even in the bosom of science, I have had to seek the back roads. Powerful methods and tools are available, but are not broadly known and widely used.

A note on crop production and soils in the Zambezi Valley

Thus far, I hope that I have done the valley and its inhabitants justice by portraying a beautiful natural resource landscape inhabited and used by local residents and immigrants. There is indeed a wealth of natural resources to which valley residents are "permitted" use. The soils of the valley in crop production are no exception. One would be hard pressed to find a household that did not have some plot of land being sown for maize, vegetables, cotton, or all three. Occurring on patches of alluvial soils in a matrix of savannah woodland, crop production has been the mainstay of Zambezi Valley economies for several centuries. Great debates have raged as to the fragility of soils in the Zambezi Valley. Many authors have claimed that cultivation will inevitably result in erosion and environmental degradation of unprecedented proportions. Others have counter-claimed that Zambezi Valley agro-ecosystems are not particularly erodible, and are well suited to crop production. Despite all this talk, no one had previously measured soil responses to cultivation in Zambezi Valley agro-ecosystems.

Using a spidergram, I asked the Village Representatives in each site to identify the most commonly cultivated soils in their areas. We then located areas of the two most commonly cultivated soils that had been continuously cultivated for at least 10 years and that abutted areas of the same soil type that had never been cultivated. Soil scientists from the Chemistry and Soil Research Institute (CSRI) in the Government of Zimbabwe's Department of Research and Specialist Services who were working with me checked that the cultivated and uncultivated areas were of the same soil type.

Knowing that great spatial variability characterized alluvial soils, we collected soil samples on a grid that was centered on the boundary of the field and the uncultivated area. Samples were taken for physical and chemical analysis; others were collected to estimate erodibility under simulated rainfall conditions. In all, we removed > 35 tons of soil from the valley for testing, although I confess that I did not include that form of erosion in my calculations! The CSRI laboratories in Harare processed the hundreds of soil samples, and Dr. Henry Elwell, developer of the Soil Loss Estimation Model for Southern Africa (SLEMSA), carried out tests on soil erodibility. We now know which of the major arable soils in the Zambezi Valley degrade with cultivation and which are erodible. As to the erodibility debate, some Zambezi Valley soils are among the most erodible in Zimbabwe and others are incredibly stable!

WOVEN KNOWLEDGE AND COMPUTER SIMULATIONS

How does a "family" of spidergrams with detailed data enhance our understanding of agro-ecosystem structure and function? Is it possible to move toward a more predictive understanding rather than just another descriptive analysis? Simulation modeling is the great integrator and the great testing ground for what we know. You cannot pretend to know when you must write a piece of computer code to make something work. Trying to write code to simulate household decision making made me realize that Allan Low's model and, in fact, the neo-classical economics model of perfectly informed and capable decision makers, were far off the mark. How was I to write code that would simulate the decision of each household member to seek off-farm work or not? Low's model required that I take expected wage rate information from all of the possible employment situations outside of Masoka (or any of the other agro-ecosystems with which I was dealing). The code would then need to compare these with expected earnings from activities on the farm and then have the household member make a decision about off-farm employment or another season of growing crops and keeping cattle, chickens, and goats. I found it almost impossible to conceive of gathering all of this information and mastering calculations, even with modern technology at my disposal. Could I realistically expect people that I had worked with to do the same? I doubted it. Low's model was useful, but not right for this task!

I have started building a second-generation simulation model of a Zambezi Valley agro-ecosystem, incorporating much of what I have learned after completing the first version in mid-1993. The approach and understanding that I have been developing have been iterative. I started with a simple model (i.e., understanding) that emerged from my readings of the literature, from discussions with scientists, managers, and government agents, and from my intuitive understanding and observations of people and ecosystems. I went into the field to collect information, data, and knowledge to test this understanding, updating my simple model. When the data collection procedure was halted, I set about building a model that would enable me to manipulate my understanding. In so doing, I found several gaps and weaknesses. I then designed a second round of field data collection to fill in the gaps and to confront the new understanding. As before, the model or understanding was updated through the process of data collection. I have just now started on the second round of modeling, bringing my current level of knowledge together in a coherent form that I can then manipulate and test. The models that I will now describe are, to some extent, redundant. Their representation of agro-ecosystem affairs is no longer current. Many of the problems that I faced, however, and the approach and principles that I developed and adopted, are still relevant and will serve to illustrate the process.

It is worth reflecting on the state of modeling agro-ecosystems, farming systems, or rural communities in southern Africa at the time when I embarked upon agro-ecosystem model development. At that time, no one had published a model that reflected even vaguely, I believe, the realities that I have illustrated in this essay. In fact, there were virtually no models, let alone systems models. Some work had been done in other parts of Africa, but these models were generally of a single enterprise or of several enterprises with only one household. Linear or mathematical programming seemed to be the way people were "doing" models. The most comprehensive work was that of economists like Alan Low on economic models of households. I felt uncomfortable with the way these models treated households as perfectly rational, independent, and homogenous entities with the computational skills of a supercomputer. In these models, household members were treated as identical robots running identical software and producing identical products! Households were not independent and they were not all the same. They form part of a community that shared ideas, ideals, resources, values, labor, seed, and equipment among a host of other things. These agro-ecosystems had to be modeled as systems comprising multiple and heterogeneous agents or households. The economists tended to use aggregated or average values for yields, prices, and inputs. This seemed to me to deny the very essence of Zambezi Valley agro-ecosystems: variability and uncertainty.

I believed that the models needed to be spatially explicit; people lived in a spatial world, and spatial processes such as fire or erosion stimulated major changes in the agro-ecosystem. I also believed that the models had to be stochastic. Literature on the emergent properties of systems suggested that critical changes might arise from even slight changes in the configuration of a system. Fires had a high probability of burning much of an agro-ecosystem where grasslands made up more than a critical threshold of the area. Chance events and current configurations could lead to entirely different final systems or states.

HOMZ (NOT FOR SPIDERS!)

I began developing HOMZ (the HOusehold Model of Zambezi Valley agro-ecosystems) early in 1993 and had a version running by the middle of that year. Its purpose was to integrate what I knew about the

Masoka agro-ecosystem and to provide a tool for manipulating this knowledge to identify which structures and processes were key determinants of agro-ecosystem performance. HOMZ included social, economic, and ecological performance measures, in fact, comprising three models. The first was a simple rainfall generator that randomly generated annual rainfall amounts in which long-term mean and variance matched the pattern of rainfall measured near Masoka. Second, an initializing model generated households and placed them on a digital map of Masoka, complete with fields and family structure. Such household characteristics matched the patterns observed in Masoka. Lastly, there was the main HOMZ model itself, in which the production activities of up to 300 households, as well as the effects of these activities on household and ecosystem well-being, were simulated. The initialization model essentially re-created the Masoka community. Rather like a board game, the model set out the players on a digital map of Masoka. Once initialization was complete, the game of life in the simulated Masoka could begin ... .

The "board game" consisted of a scaled-down version of a three-dimensional map of Masoka. The 14 km^2 area that I used for the simulations was cut up into about 3500 cells, each representing a bit less than 0.5 ha of the real Masoka. Each of these cells had attributes of slope, soil type, and vegetation cover. The initialization model placed households on this digital board or map. It sought to locate households as they would locate themselves; flat sites with stable soils close to the Angwa River were usually selected first. Each household was allocated fields around the home site, just as in Masoka. The initialization model produced a scaled digital replica of the Masoka community that I could easily observe. A major difference was that in the digital version, I, like a myopic but curious god, could control where people lived and what resources they had at their disposal.

The HOMZ main model was the vehicle by which control was exercised through every aspect of community, household, and ecosystem existence. Life carried on in this digital world similarly to the real Masoka, except that it was simplified and I only looked once a year at what was happening! Planned crops were planted, the rains came, and soil eroded. If soils were fertile and the rains were good, then as long as the household had sufficient labor to weed and cash to procure the necessary pesticides, their harvests were plentiful. If the rains failed, however, and the household had mismanaged its soils, then poor harvests meant that the household would have to buy food, go out to work, or go hungry! Unlike so many models that I had seen, there were direct links in HOMZ between household activities and resources. Poor management of soils led to reduced yields now and increased erosion later. Just as important, I could observe how these effects played out in a community of households varying in resources and management skills. I could alter and adjust a vast range of factors to investigate their implications for what I believed to be a reasonably accurate replica of Masoka.

Based on their needs, aspirations, knowledge, and expectations, people make decisions. Seldom, however, do things go exactly as planned; chance and unforeseen events alter outcomes and bring surprises. I am sure that we have all at one time said, "... it would have been different if only ... ." One of the most powerful and rewarding capabilities of models like HOMZ is the ability to replay "life" hundreds of times. With each replay, outcomes of the myriad of chance events are re-determined as if by thousands of lottery draws. At the end of these hundreds of replays, the analyst is able to examine each to determine which structures or processes were important, which chance events under what conditions were influential, and which interventions were decisive and which inconsequential. This technique, called the Monte Carlo method, provided me with innumerable opportunities to explore the strengths and weaknesses of my understanding of the Masoka agro-ecosystem. It also enabled me to experiment with worlds and behaviors that were not, and might never be, a part of the "real" world.

HOMZ did prove a remarkable integrator of the disparate bits of knowledge that I had collected. It was also a harsh testing ground for my understanding of the Masoka agro-ecosystem. I soon found that I did not know enough about household decision making or how the community allocated land and other resources. Many of my calculations and simulations suggested that households could not satisfy their target need levels from crop production, yet they had been living there for decades. What was I missing? I also did not know enough about changes in technology and the adoption of new technologies. These and a host of other questions sent me back to the proverbial drawing board to design a new study that would fill these gaps and correct my many misperceptions.

Modeling increased my confidence in the approach I was adopting. Zambezi Valley agro-ecosystems need to be treated as systems comprising multiple interactive and heterogeneous households. Equally important, the modeling clearly indicated strong linkages between ecosystem function and household well-being. Different household production strategies result in different environmental outcomes. Variance in fallow cycling can result in noticeable soil fertility and/or erosion changes. This cycling, were it to occur in the real world, might result in severe and synchronous yield failures or large-scale erosion events, conditions eminently suited to unpleasant surprises!

One can spend a tremendous amount of time running and rerunning thousands of simulations. It is worth remembering the words of the renowned statistician, G. E. P. Box, "All models are wrong, but some are useful." How can we be confident that our models are correct and are not leading us toward some immensely rich, but ultimately misguided, perceptions? This important question is difficult to answer satisfactorily. There is no satisfactory way to validate the predictions of models as complex as HOMZ. I have tested all of the main model components using standard procedures of comparing simulated and observed data. Each component performed within acceptable boundaries when tested as a stand-alone component. Yet, how could one gather data to test the predictions of the model as a whole? Even if it were possible, the complex interactions between "social" components and the environment mean that the observed state of a real system might have originated from several different combinations of events and states. Validation is indeed a thorn in the side of modelers of complex systems.

I reject the classical scientific notion that models are binary: either right or wrong. I see, rather, the process of validation as confronting models with data, other forms of knowledge, and logical reasoning. Through this iterative confrontation between models and knowledge, the models and our confidence in them are updated or improved. Very often, the usefulness of models is in forcing us to come to terms with what we do not know, rather than in making specific predictions about the future. I use a simple rule of thumb. If I cannot manipulate a problem in its entirety in my head, then I need a model to do it for me. With any of the Zambezi Valley agro-ecosystems that I have examined, I could not even manipulate a model of a single household in my mind, let alone 300 households interacting in a variable and uncertain environment! Models and modeling are an important part of the toolbox needed to analyze Zambezi Valley agro-ecosystems. They are not the sole tools nor are they an end in themselves. They provide focus, integration, and a remarkably powerful means of examining what we know and recognizing what we do not.

CURRENT IMAGES OF ADAPTIVE SYSTEMS AND AN EVOLVING PROCESS

Ultimately, the test of my research and the approach that I have developed should be answerable to the following questions. Do we know more about Zambezi Valley agro-ecosystems than we did before our investigations? Do we have improved methods, tools, or theory with which to investigate systems like Zambezi Valley agro-ecosystems? Is the knowledge that we have obtained accessible to agro-ecosystem policy and decision makers, and can they use it to improve their management or policy making? How would we know what type of impact, if any, this knowledge has had on agro-ecosystems? Over the past few years, I have come to recognize that our knowledge of Zambezi Valley agro-ecosystems is limited and that our ability to predict what they will be like 5-10 years down the road is sadly undeveloped. With that in mind, I offer some of the lessons I have learned along this journey, in hope that they will form the foundation on which future research is based.

- Zambezi Valley agro-ecosystems are evolving and adaptive. The analytical and theoretical tools we use should at least be capable of dealing with these realities. Economic theories of evolving and adaptive agents and institutions, and theories of hierarchically structured and adaptive ecosystems, are likely to provide more meaningful insights than theories of economic or ecosystem equilibrium.

- A mixture of private, quasiprivate, common, and open-access property rights governs Zambezi Valley agro-ecosystems. Few of the goods and services produced or used are traded in markets. Political and legal institutions or organizations are new, experimental, and weak. When institutions are weak, individuals can have enormous impacts for good or ill. Theories of institutional economics and political economy are likely to provide tools that are better suited to these conditions than would neoclassical economics.

- Hydrology and hydrological processes are crucial determinants of the structure and functioning of Zambezi Valley agro-ecosystems. Our understanding of these processes in large, variable landscapes is poorly developed. The role of rivers in local economies and in maintaining the productivity of Zambezi Valley ecosystems is a major gap in our understanding.

- Wildlife and livestock populations have important impacts on household well-being and on ecosystem structure and functioning. They impact ecosystems at different scales than those at which crop production impacts an ecosystem. Multiscaled investigations and modeling are essential precursors to understanding Zambezi Valley agro-ecosystems.

Although I have learned a great deal methodologically and theoretically, agro-ecosystems analysts still face challenges that I believe are somewhat daunting; I list a few.

- In general, we take measurements or observations at discrete scales, but the structures and processes we are observing shift along a continuum. The challenge of integrating structures and processes that cross multiple scales and disciplines is one of the most difficult we face.
- Scientists, policy makers, and even Zambezi Valley residents are more inclined to believe the numeric predictions of science than other forms of knowledge, even if the former are less reliable! A major challenge in the analysis of Zambezi Valley agro-ecosystems is to integrate the many forms of knowledge that we use without biasing the resulting understanding. The weights attached to different forms of knowledge should be based on our confidence in each bit of knowledge and not on its source or the symbolic structure used to represent it.
- In combining knowledge from multiple sources, we include multiple and heterogeneous sources of uncertainty. A major technical challenge is the way in which the combination of these different sources of uncertainty and their propagation through computer simulation models should be analyzed and expressed.
- Given the variability in our world, our limited ability to measure or observe such, and the uncertainties introduced by our analytical methods, how do we develop confidence in our knowledge or understanding of the world?
- A vast majority of the agro-ecosystem managers in the Zambezi Valley have never seen a computer. On average, they may each have completed only 7-8 years of school. Translating complex simulation models into symbols and concepts that nontechnical people can understand and feel comfortable with may prove to be one of the most difficult challenges of all.

Over the past eight years, I have developed some general principles or rules of thumb that form the basis of the DAAWN perspective. In a simple way, they capture the essence of my approach to agro-ecosystem analysis. DAAWN is not, and *should* not be, the only approach to these difficult problems. At a minimum, analysis should be conducted at three scales: the scale of interest, one scale up, and one scale down. Track the big picture. Watch the details and expend most effort where the payoffs are highest.

I further believe that the situation or problem should define the boundaries and level of detail to the problem at hand, rather than adapting the problem to the available set of tools and methods. Finally, knowledge is widely distributed among system stakeholders. Science does not have a monopoly on knowledge or understanding.

SPINNING A NEW WEB

I have described the beginning of a long, exciting journey. In many places, I have had to build the road myself. In others, I have benefitted from the Herculean efforts and ideas of those who traveled this path before me. Every so often, I dimly glimpse other shadowy figures on some distant part of the road or on some intersecting route. Knowing that I do not travel alone gives me faith. But what do I see on the road ahead?

I believe that there are three components to the study of complex systems. The first is science: the philosophy, methods, tools, and theory. The second component is communication: the message and the media. The third component is how we organize science and communication. I will briefly describe my vision for each of these three components and explain why I am increasingly inclined to believe that the three are inseparable.

Much of this essay has dealt with the science of analyzing complex systems, based on my experiences with Zambezi Valley agro-ecosystems. I have explained why it is so difficult to predict the future state of these systems, and have described my approach in developing a predictive understanding of them. During fieldwork and modeling integration and reiteration, I have sought first to avoid the ever-present danger of developing theory that has lost its connection with reality. Such theory is of little use. Second, and equally important, I believe that the real world is by far the best testing ground for theory.

I believe, too, that the science of complex systems likely to emerge over the next few decades will only vaguely resemble the practice of science as we now know it. Every aspect of science and its practice will have to be rethought and reworked; from philosophy to delivery of results, the rules of science will be rewritten. I am sure that many elements of what is now on the fringe of science will be part of the mainstream in the science of complex systems. Tools and theories that deal with uncertainty, such as fuzzy set theory and Bayesian statistical theory, will become a part of the essential toolbox with which complex systems analysts work. I suspect that in its metamorphosis, science will forge new alliances, particularly with the business community. Market analysts, industrial psychologists, advertising agencies, and the like have a wealth of practical experience that, in combination with the scientific community, could generate exciting new insights into the analysis and management of complex systems.

Modes of communication across a diverse spectrum of systems stakeholders are changing. It is exciting but deeply disturbing. The availability of Internet information expands the home computer to the four corners of the developed world. The rural poor of southern Africa, however, may still be without electricity 10 years from now. Will the information age empower them in any way or just increase the great divide between those that have and those that do not? With information comes power: economic, social, political, and cultural. Perhaps the Internet will deliver information to rural people of southern Africa as no technology has before. These rural people currently manage > 80% of the ecosystems of southern Africa. Can we help without harm? Can we deliver to them appropriate tools and information and teach them their use so that they can effectively manage their resources to meet their needs and those of their children? Dare we dream of politicians in the north listening while the people of the Zambezi Valley tell them how Africa's savannah resources should be managed?

With increasing globalization has come a massive increase in the stakeholder communities that we need to consider and consult. Managers, program officers, or administrators in Washington, Geneva, or Berlin are expected to administer programs and projects to meet the needs of people and ecosystems in the farthest reaches of the globe. There seems to be little evidence that they have been successful; the poor are still agonizing and ecosystems are still vanishing.

Together with new approaches to science and communication, I believe that we need new methods of organizing the way in which we practice science and deliver its products. In an adaptive, changing world, adaptive and flexible organizations make the most sense. I believe that scientists, development specialists, and policy makers have much to learn from the organizational structures of modern corporations, particularly those dealing with computer technology and information dissemination. I have faith that we *will* structure our activities to better understand, manage, and design locally complex systems in a globally complex world.

RESPONSES TO THIS ARTICLE

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