LINKING SOCIAL-ECOLOGICAL SYSTEMS AND LAND-USE LAND-COVER CHANGE THROUGH A COMPLEX ADAPTIVE SYSTEMS APPROACH: A CROSS-BORDER STUDY OF SISAKET, THAILAND AND ORDAR MEAN CHEY, CAMBODIA

By

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To the memory of my father, Donn Cassidy

I like to think he would have been proud of me

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By

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The social-ecological systems (SESs) and land-use land-cover change (LULCC) research programs represent two responses to our need to understand the complexity of human-environment interactions that are driving change at a global level. SESs research has, however, struggled to find ways to quantify broad-scale system processes, while LULCC research has been unable to express its patterns of change in a way that allows cross-site comparison. This dissertation argues that complex adaptive systems (CASs) theory can be used to link SESs and LULCC research. It shows that LULCC, when considered as the tangible expression of an SES, presents an opportunity to measure and quantify the effect of system processes. CASs theory, as used in SESs research, provides the abstraction necessary for extrapolating and predicting LULCC, even in highly dissimilar systems. The concept of diversity, among other CAS characteristics, can be applied to LULCC, allowing systems to be represented as landscapes of land-use land-cover (LULC) diversity, which can then be mapped, measured and contrasted in different study sites.

This research introduces the concept of LULC diversity, as embedded in the framework of CASs, and defines the methodology needed to show how LULC diversity has the potential to

allow researchers to find commonalities across a range of different social-ecological systems (SESs). A case study of the adjacent, but different landscapes of Sisaket province, Thailand, and Ordar Mean Chey province, Cambodia is used to test whether the spatial and temporal patterns, as well as the frequency distributions of LULC diversity provide meaningful information of the landscape. Finally, known factors influencing LULC change are used to predict change in LULC diversity instead of in actual LULC types, to determine whether there are general trends in the response patterns of LULC diversity regardless of system type.

Results show that not only is LULC diversity visible as distinct patterns on the landscape, but also that these patterns relate to known features and areas of change – regardless of system type. While the two SESs do indeed exhibit the same directionality in the responses of their levels of LULC diversity to the different factors, the differences in their biophysical and socio-economic characteristics result in different strengths of relationship. The findings of this research suggest that LULC diversity reflects the dynamic complexity of the human-dominated landscape. It responds in measurable ways to different factors influencing LULCC. The spatial arrangement of LULC diversity can be used as a means to quantify change in SESs. As such, it provides a means of abstracting landscapes so that comparisons can be made between landscapes and SESs that would otherwise be context-dependent.

CHAPTER 1
INTRODUCTION

This dissertation introduces and tests a theoretical framework and set of methods for uniting two existing research programs that address landscape-level change. Specifically, I draw on the theory of complex adaptive systems (CASs) that is used in social-ecological systems (SESs) research, and combine it with the methods used in land-use land-cover change (LULCC) studies. This allows the strengths of each program to complement the other. The research is presented as three separate papers, presented in publication style for submission to academic journals. Each paper is therefore a stand-alone document, addressing different aspects of the research problem described below. The first, "Quantifying Social-Ecological Systems through Land-Use Land-Cover Change: A Complex Adaptive Systems Approach" introduces the two research programs, and shows the applicability of CASs theory. The second paper, "Patterns of Land-use Land-Cover Diversity as Complex Adaptive System Components: A Cross-boundary Comparison of Two Provinces in Thailand and Cambodia" applies the theory of complex adaptive systems (CASs) generally, and the concept of LULC diversity specifically, to the description of landscape change in the cross-border provinces of Sisaket, Thailand, and Ordar Mean Chey, Cambodia. The third paper, "Social and Ecological Factors and Land-use Land-cover Diversity in Two Provinces in South-east Asia" tests the response of LULC diversity in Sisaket and Ordar Mean Chey to factors known to influence the distribution of different LULC types.

Statement of the Problem

The processes affecting the dynamics of social-ecological systems tend to be hard to describe, challenging to model, and even more difficult to quantify and measure. This is in part because of the complexity of such systems (O'Neill 1999; Ludwig, Walker, and Holling 2002;

Chave and Levin 2002; Gibson, Ostrom, and Ahn 2000; Allen and Starr 1982). More particularly, some of the concepts are hard to translate into tangible indicators. Resilience, for example, is difficult to quantify because to some extent it is a relative condition contingent upon earlier states and future perturbations (Carpenter et al. 2001; Cumming et al. 2005). Consequently, researchers are struggling to develop methods to quantify the within-site and cross-site heterogeneity and complexity inherent in SESs. The challenge then, is to identify what quantitative data could provide a suitable representation of human-environment interactions in a given system.

Whereas SESs research developed under the umbrella of a conceptual framework, LULCC studies first document case studies, and then search for theoretical models to explain the relationships they have found. Currently, however, researchers have yet to advance LULCC studies to a point where these theories explain a range of conditions. This is largely because the complex nature of the social and ecological interactions underlying LULCC is a challenge to the post-hoc development of a universal deductive research approach (Bürgi, Hersperger, and Schneeberger 2004). Even within the same LULC system, theories remain context-specific (Perz 2007). Researchers have found that the complexity of interactions makes it difficult to extract general characteristics from their case studies for comparison and application in other contexts (Briassoulis 2000; Rindfuss et al. 2004). Consequently, LULCC studies still lack a cohesive, trans-disciplinary framework on which to base their questions. With a more solid, generalized theoretical foundation and a better understanding of mechanisms, LULCC analyses would be able to provide planners and managers with more reliable predictions.

Linking Research in Social-Ecological Systems and Land-Use Land-Cover Change: A Complex Adaptive Systems Approach

The first paper, presented in Chapter 2, provides the conceptual linkages between SESs and LULCC, and details the characteristics of CASs and how they apply to LULCC. The underlying assumption is that, by treating the patterns of LULCC as tangible expressions of a SES, we can firstly transfer the concepts of CAS to LULCC, and secondly use this spatially explicit, area-based form of analysis as the basis for quantitative assessments of SESs.

In this chapter I describe the current states of SESs and LULCC research, and detail the challenges that each face. I then introduce CASs, highlighting key characteristics, and applying these conceptually to the study of LULC. Next, one key CAS characteristic – diversity – is focused on for the development of the research framework necessary to test the effectiveness of this approach. Specifically, it addresses the utility of the concept of diversity, as embodied in CAS theory, as a way of generalizing the components of different SES/LULC systems so that they can be compared. The framework and methods detail how researchers can a) describe, map and measure the distribution of LULC diversity across landscapes, b) evaluate the patterns of LULC diversity in response to biophysical and socio-economic factors known to influence LULCC, and c) assess change over time in LULCC diversity in response to those different processes.

Patterns of Land-use Land-Cover Diversity as Complex Adaptive System Components: A Cross-boundary Comparison of Two Provinces in Thailand and Cambodia

In Chapter 3, I use a cross-border comparison of the study area provinces to test whether LULC diversity has distinct frequency distribution patterns, and whether spatial patterns of LULC diversity are visible in the landscape. I focus on diversity as a key CAS concept and as the main characteristic that underpins the complexity of human-environment interactions central to both the LULCC and SESs research programs.

In order to test LULC diversity as a unifying, non-ecosystem specific characteristic for cross-site comparison, we need to show it as non-random, presenting distinct patterns on the landscape at different scales, with different magnitudes of diversity dominating at different locations, and with meaningful variation in magnitudes of diversity over time. I use the following guiding questions to carry out this analysis:

- What is the distribution of LULC diversity across two different landscapes?
- What magnitudes of LULC diversity dominate in each landscape?
- What happens to the LULC diversity of an area over time?
- How do the patterns of diversity compare between the two landscapes?

The distribution of LULC diversity is different for both provinces and at different scales. While there is temporal variation, the distributions for each province and scale maintain similar patterns over time. The spatial arrangement of the LULC diversity patterns suggest that the spatial distribution is responding to the influence of drivers such as markets, roads, elevation and slope, and that the response of LULC diversity to these mechanisms should be tested.

Social and Ecological Factors and Land-use Land-cover Diversity in Two Provinces in South-east Asia

In order for the concept of LULC diversity to prove itself meaningful in both LULCC and SESs research, it should respond to the same biophysical and socio-economic factors that are known to influence the distribution of individual LULC types. The purpose of Chapter 4 is to test those responses in two provinces in south-east Asia to see a) whether LULC diversity changes with known factors influencing change in individual LULC types, and b) how the actual relationships between LULC diversity and elevation, distance to roads and distance to market compare to those hypothesized in Chapter 1. Spearman’s rank correlations were run to establish general relationships for the entire landscapes at three scales. Because the explanatory mechanisms are scale-dependent, functions approximating the hypothesized distributions were tested against micro-scale LULC diversity only. Distribution maps of LULC diversity as predicted by each factor were subtracted from observed LULC diversity, to create maps show where the models worked well or not.

The study shows that for the most part, LULC diversity at all scales increases as elevation, distance to roads, and distance to market decreases. At the micro-scale, the distribution of LULC diversity in response to elevation and distance to market bore a general resemblance to the schematic diagrams of the hypothesized relationships. However, LULC diversity did not match the predicted distribution shape in its response to distance to roads, and this hypothesis should be modified. These findings confirm the utility of the LULC diversity concept as a generalization that supports cross-site comparisons between dissimilar landscapes, and a way of integrating SESs and LULCC research.

Importance of the Study

Together these three papers contribute to the development of a research framework for the study of human-environment interactions that is founded on both theory and empirical measurement (Bürgi, Hersperger, and Schneeberger 2004; Kuhn 1996; Walker 2004). The approach outlined in this dissertation makes the link between SESs and LULC explicit, and supports the emergence of LULCC analysis as a science (Rindfuss et al. 2004). It also introduces techniques to quantify the generalized system characteristics that define SESs, and shows how some of these can be measured (Carpenter et al. 2001; Cumming et al. 2005). This research represents initial steps in evaluating CASs as a generalized, quantifiable theory of human-environment interactions. It is hoped that the work presented here will stimulate interest in other researchers to further test and expand on the ideas they contain.

CHAPTER 2
LINKING RESEARCH IN SOCIAL-ECOLOGICAL SYSTEMS AND LAND-USE LAND-COVER CHANGE: A COMPLEX ADAPTIVE SYSTEMS APPROACH

Introduction

The purpose of this paper is to bridge two existing research programs that address landscape-level change under a single theoretical framework and approach. Specifically, the aim is to draw on the theory of complex adaptive systems (CASs) that is used in social-ecological systems (SESs) research, and to combine it with the methodology used in land-use land-cover change (LULCC) studies. This will allow the strengths of each program to complement the other. By linking the two research programs, LULCC analysis will gain access to the conceptual strengths used in SESs research, while SESs analysis will be able to use the quantitative methods that underpin LULCC research. CAS theory is generalized, and its context-independent characteristics can be used to understand landscape dynamics in different places. Just as species are all different at the level of the organism, but comparable at the level of organ, tissue, cell or DNA, so too are landscapes. Landscapes differ from each other because the specific combination of components (including people), ecosystems, climate, culture, etc. is unique for each – but all landscapes will contain these components.

The LULCC and SESs research programs can be seen as two views addressing the same issue: both aim to understand the processes underlying environmental change, and both emphasize the role of humans as agents and recipients of that change. However, each of these views takes a different approach and provides a different perspective on human-environment interactions. While LULCC analysis has focused on mapping, describing and explaining changes in the Earth's cover, SESs research addresses the flows of energy and information between system components (Gunderson and Holling

2002; Turner et al. 1995). As a result, each research program tends to comprise a different community of researchers, each using different frameworks and vocabularies, and the collaborative efforts along these closely parallel paths have to date been few (Lambin et al. 2001; Schweik, Evans, and Morgan 2005 represent the exceptions).

A system can be defined as a set of components and the interactions between those components. A SES considers the way humans interact with their environment, not only in terms of direct use of food and resources, but also in terms of the policies, cultural practices, and institutions that influence where and how we make use of different aspects of the environment. Most of our interactions occur on the surface of the earth, and our activities leave distinct spatial patterns, such as the geometric blocks of fields or the node-spokes of settlement-roads on the landscape. The changes in these spatial landscape patterns are one of the key things that LULCC researchers measure to determine the extent of human influence on the environment.

This paper proposes that by treating the patterns of LULCC as tangible expressions of a SES, we can firstly transfer the concepts of CAS to LULCC, and secondly use this spatially explicit, area-based form of analysis as the basis for quantitative assessments of SESs. Linking the two approaches is a key step in the search for generalization at fundamental landscape levels. The underlying assumption of this proposed linkage is that, by viewing LULCC as a physical manifestation of the system, we should be able to represent change in the condition or state of the SES.

In this paper I first describe the current states of SESs and LULCC research, and detail the challenges that each face. I then introduce CASs, highlighting key characteristics, and applying these conceptually to the study of LULC. I next focus on diversity as the key element of CASs, and as the starting point of generalizing landscapes. Finally, I show how patterns of LULC diversity can be mapped and measured, and suggest how the distribution of LULC diversity might respond to biophysical and socio-economic drivers known to affect LULCC.

Social-ecological Systems

SESs are by nature complex. Even where humans have become separated from direct production and consumption of natural resources, we effect, and are affected by, global climate change and the rapid spread of chemical compounds (Folke et al. 2004; Vitousek et al. 1997). Wherever we live, we are dependent on the services that the environment provides (Costanza et al. 1998; Swift, Izac, and van Noordwijk 2004). The theoretical foundation of the SESs research program builds directly on systems approaches as used by ecologists, but specifically includes humans and their socio-cultural processes into the system definition. At any one point in time, researchers are studying property rights, land tenure systems, world views, ethics, economics, climate, soils, abundance of organisms, and how all these factors affect each other (Berkes and Folke 1998).

A key area of research is variability in systems. This focus is built on a concern for sustainability – as humans, we have an interest in seeing desired conditions of certain landscapes continue or persist in the long-term. Over the years, scientists and managers have come to appreciate that short-term fluctuations form part of a system's long-term identity, and affect not only humans, but also plants and animals. For example, we understand the annual shift from hot, dry summer to cold, wet winter to be part of the identity of a Mediterranean climate. While seasonal variation represents an example of predictable change, the concern for managers is also how to accommodate unpredictable change, and whether a system can remain the same after an external shock or perturbation, or whether it changes so much that it should now be considered to be a new system (Berkes and Folke 1998; Holling and Gunderson 2002).

The ability of a SES to persist and maintain its general structure and same functioning in the face of external perturbations is known as its resilience (Carpenter et al. 2001; Holling 1973). It is largely through this concept that SESs research addresses the issue of sustainable resource use. A simplified example of this would be the case of the tropical forests in the Brazilian Amazon. Whereas the extraction of a few trees to build homes for indigenous people living in the forest has little impact on the forest, the large-scale clearing for commercial farming and logging for export markets represents a perturbation that has seen large parts of the forest converted to farmland. Overall, much of the Amazon retains its identity as a tropical forest, but in many areas at a more local level, the identity of 'forest' has given way. The notion of resilience is important because it draws attention to the fact that SESs move through a range of conditions or multiple stable states and are subject to a range of internal and external disturbances. Any management of a SES to maintain a desired state in the long-term needs an understanding of how dynamic and complex the interactions are in the SES under investigation (Berkes and Folke 1998; Folke et al. 2004).

Recognition of SESs as CASs is implicit in the concept of resilience, and explicit in the SESs research program (Holling 2001; Janssen, Anderies, and Ostrom 2007; Levin 1999; Walker and Abel 2002). This is because many of the key characteristics of CASs (as elaborated below) are important factors determining whether a SES is sustainable and able to persist or not. Some of the factors that might affect whether a system is able to maintain its functioning might be how abruptly change occurs, whether that change occurs at a local level or a more regional level, whether several factors occur at the same time (such as fire, drought and over-grazing), the history of land use over the past few decades, and the individual land-use decisions made by people might lead to a distinct, collective agricultural landscape (Cumming and Collier 2005; Holling and Gunderson 2002; Janssen, Anderies, and Ostrom 2007; Levin 2003; Odum 1975). The use of CAS theory to understand SESs has been applied in a range of settings, with notable case studies in lake districts, ocean fisheries, and savanna rangelands (Carpenter et al. 2001; Gross et al. 2006; Janssen, Anderies, and Walker 2004; Walters 1986; Wilson 2006).

Challenges to SESs Research

Although many researchers within the SESs research program already draw on CAS theory, much of its use has remained conceptual, and the measurement of change in SESs has remained elusive (Brock and Carpenter 2006; Carpenter et al. 2001; Cumming et al. 2005). This is in part because the processes that affect the dynamics of social-ecological systems tend to be hard to describe, challenging to model, and even more difficult to quantify and measure. With most SESs being so very complex, it has been difficult to identify concrete system components that can represent sufficient aspects of the SESs in ways that allows the critical, but somewhat abstract, CAS characteristics to be measured. Processes have synergistic effects (O'Neill 1999), or occur at a scale that makes them hard to detect at the scale of observation – whether spatial or temporal (Chave and Levin 2002; Gibson, Ostrom, and Ahn 2000; Allen and Starr 1982), or the system will have multiple stable states (Ludwig, Walker, and Holling 2002). More particularly, some of the concepts, such as resilience, are hard to translate into tangible indicators, as to some extent this is a relative condition contingent upon earlier states

(Carpenter et al. 2001; Cumming et al. 2005). Consequently, researchers are struggling to develop methods to quantify the within-site and cross-site heterogeneity and complexity inherent in SESs. The first challenge then, is to identify what quantitative data could provide a suitable representation of human-environment interactions in any or all SESs.

Furthermore, SESs research tends to have a localized geographical focus. This is a consequence of its origins at the ecosystem level. The generalized abstractions (such as sustainability and resilience) used to describe SESs have been applied to systems of limited extent – even where these might be referred to as "large-scale" (Gunderson and Pritchard Jr 2002). Many of the processes underlying complex SESs occur at even broader scales, across landscapes comprising several ecosystems and several communities (Crawford 2005). The implication is that is that some of the higher-order, regional and global impacts of human-environment interactions are being missed. This second challenge to SESs research is one that most clearly highlights the opportunity for drawing on existing landscape-level approaches to human-environment interactions: LULCC research.

Land-use Land-cover Change

LULCC analysis is an emerging science that aims to document and explain the local- and regional-level changes to the earth's surface, which, through their cumulative effects, also have global-level consequences (Lambin et al. 1999; Rindfuss et al. 2004; Vitousek et al. 1997; Ojima, Galvin, and Turner 1994; Houghton 1994). The LULCC research program arises directly from the realization of the potentially dramatic consequences of global-level changes, and the need to understand the dynamism and spatial and temporal variability inherent in human-environment systems (Arrow et al.

1995; Lambin et al. 1999; Foley et al. 2005; Houghton 1994; McMichael et al. 1999; Ojima, Galvin, and Turner 1994; Turner et al. 1995).

LULCC research focuses on the dynamic interactions between human uses of landscapes – that is, land use –and the Earth's biophysical conditions, as reflected by land-cover. The stated objectives of LULCC research has been to document and measure change in land cover, and to explain "the coupled human-environment system dynamics that generate these changes" (Rindfuss et al. 2004 p 13978).

LULC is far more than just a way of describing human activities – it represents a dimension of system functioning, and can be seen as a tangible expression of human-environment interactions. In a human-dominated landscape, the type, shape and location of land cover often correlate with how the land is – or is not – being used. LULCC is commonly understood to be the result of a range of biophysical and socio-economic drivers, with proximate drivers having greater influence than distant ones (Wood and Porro 2002). In other words, the patterns of LULCC that we see across the landscape are largely the result of the interplay between socio-economic and biophysical processes. Some examples of these interactions include scrub encroachment due to the suppression of fire and increase in grazing (Roques, O'Connor, and Watkinson 2001; Wiegand, Saltz, and Ward 2006), changes in hydrology due to montane afforestation (Farley, Jobbágy, and Jackson 2005; Gallart and Llorens 2004), migration due to land degradation (Markos and Gebre-Egziabher 2001; Henry et al. 2004), and tropical deforestation due to market demands for hardwood timber or agricultural produce (Geist and Lambin 2001; Lambin, Geist, and Lepers 2003).

As with SESs research (and befitting such relatively young research approaches), most LULCC analyses have focused on case studies – first documenting, and then modeling various socio-economic and biophysical interactions. Simulated modeling has moved from describing current interactions to predicting future states as the body of knowledge has grown (Briassoulis 2000; Parker et al. 2003). With sufficient case studies now documented, LULCC researchers are beginning to put forward generalizations that can be used in deductive research. This is in contrast to the SESs approach, which started with theoretical generalizations, which were then explored through different case studies.

Among LULCC researchers, one of the primary generalizations that has emerged is that of accessibility, that is, how easily humans can get themselves, and their resources, from place to place. This emphasis on accessibility within the LULCC research community indicates the magnitude of human impact that overshadows all other social-ecological interactions. Based originally on Von Thünen's 1826 rent-bid model of access to markets, accessibility has been tested as an explanatory variable for deforestation, agricultural intensification and urbanization in a growing number of studies; see for example Kim, Mizuno, and Kobayashi (2003); Southworth and Tucker (2001); Verburg et al. (2002); Walker (2004b); Liu (1999); Walker and Soleki (2004). Von Thünen's work also forms the basis for LULCC studies relating to the economics of land values and distance to market (Liu 1999; Walker and Soleki 2004). Economic geography, which is founded on location theory, has provided the strongest contribution to LULCC theory (Irwin and Geoghegan 2001; Walker 2004a). It tends to be empirically based, and draws on ideas of utility, uneven accumulation, technological evolution and institutional economics (Briassoulis 2000; Martin 1999). Economic geography has also been central in the development of models, perhaps because of its empirical focus, and because economic characteristics and decisions tend to be more readily quantifiable and captured as indicators (Parker, Berger, and Manson 2001; Parker et al. 2003).

Although economic geography has been the source of much of the theoretical development of the LULCC research program, accessibility and economics alone do not explain enough of the observed changes in land use in all cases (Cromley 1982). There has been a growing recognition that individual behavior, policy and institutions, culture, demography and level of technological development also affect the type and intensity of LULCC (Briassoulis 2000; Geist and Lambin 2001). Additional theories based on human-environment interactions, as observed by different disciplines such as economics, ecology, sociology, have been called into use at the case study level. These theories focus on population growth (e.g. Malthus), rural development (e.g. Boserup), and political ecology, inter alia; see for example (Briassoulis 2000; Entwistle et al. 1998; Kummer and Turner 1994; Ostrom et al. 1999; Pan et al. 2004).

The empirical basis of its analyses has been one of the underlying strengths of LULCC research. Not only have most case studies consisted of quantitative assessments of change, but most also tend to be spatially explicit. This allows for the location of the system in space and time to be taken into consideration and for the patterns and processes of that system to be linked to conditions related to a given geographic position. It also means that change over time can be linked to spatial variability in large, slow-moving regional processes (Lausch and Herzog 2002; Turner, Gardner, and O'Neill 2001). In addition, this spatial approach means that LULCC research has been able to map, measure and model environmental change using geographic information systems (GIS) and remote sensing, whose birds-eye view lends itself to the detection of landscape patterning (Jensen 2000).

Challenges to LULCC Theory

Whereas SESs research developed under the umbrella of a conceptual framework, LULCC studies have first documented the problem, and then searched for theoretical models to explain the relationships they have found. This has hampered the post-hoc development of a universal deductive research approach (Bürgi, Hersperger, and Schneeberger 2004). Researchers have found that the variability and complex nature of the social and ecological interactions underlying LULCC have provided a challenge to their ability to develop generalizations, and to predict accurately the extent, nature and even direction, of change (Briassoulis 2000; Rindfuss et al. 2004). As such, even within the same LULC system, theories remain context-specific (Perz 2007), or one-sided, reflecting the disciplinary origin of the researcher (Irwin and Geoghegan 2001). Consequently, LULCC studies still lack a cohesive, multi-disciplinary framework on which to base their questions (Perz 2007; Rindfuss et al. 2004). With a more solid, generalized theoretical foundation, LULCC analyses would be able to provide planners and managers with more reliable predictions.

For LULCC researchers then, the next step is to move away from viewing the complexity of LULCC as an obstacle, and to embrace it – as SESs researchers have done. In order to generalize across regions, LULCC researchers need to move beyond the specifics of a given system, such as how hardwood demand in the North drives tropical deforestation. Instead they should focus on describing system-neutral characteristics of systems – such as the number of processes, rather than the individual types of processes, or the degree of fragmentation, rather than what LULC types are being fragmented.

These underlying, fundamental, system-neutral characteristics are the source of generalizations. That is, LULCC researchers already have a clear idea of what drives or limits change (roads, access to market, elevation, etc.) and these factors are important in most systems. However, an assessment of the *response* to these drivers is currently limited to being based on the specific LULC type in an area – and this might vary from place to place. If LULCC researchers continue to work with the same drivers, but focus on a more generalized response characteristic, they can then compare the effects of these drivers even where the LULC types are highly dissimilar. System characteristics might vary in quantity (e.g. tropical forests sequester more carbon annually than deserts do), but not in the nature, or quality, of the variable (carbon inputs and outputs).   It is through these generalizations that an explicitly systems-based approach has the potential to give LULCC researchers a unified framework to overcome the current theoretical challenges this new field is facing.

Integrating SES and LULCC Approaches

Even though LULCC is concerned with regional and global level change, it has, like SESs research, focused on local case studies. This is largely through an appreciation of the level of decision-making that drives change – often being at the level of individual households. To some extent, the levels of analysis of the two research programs are quite well matched – and both are able to explore and describe variability at a range of scales.

Both have to deal with conceptually separated components, that is – social / land-use vs. ecological / land-cover – that pose problems precisely because they do not always represent true separations. One example is the issue of scale mismatch, where management is often hampered by trying to apply a blanket, national-level policy to landscapes that in fact comprise many local-level ecosystems (Cumming, Cumming, and

Redman 2006; Walker 2004b). As Redman et al (2004) point out, the separation into social and ecological systems is conceptual only, resulting from disciplinary divisions, more than from actual divisions in the real world. Another example is how disciplinary separation has resulted in different framing and foci of research - such as how preferences, production costs, utility and value are dealt with differently by ecologists and economists (Daily et al. 2000).

In a way, SESs and LULCC can be seen as two sides of the same human-environment coin (Figure 2-1). One describes the processes, the other captures the patterns. We can therefore view LULCC as a physical manifestation (the patterns) of the

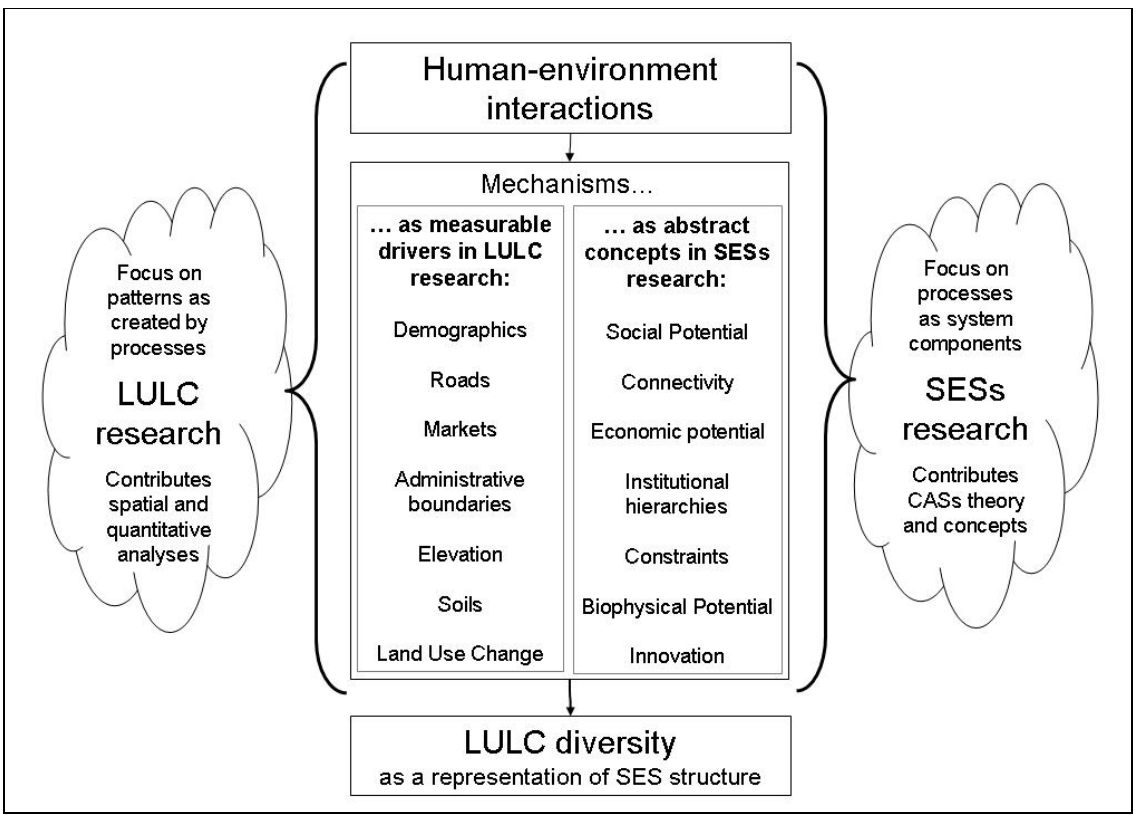

Figure 2-1. Schematic diagram showing how the divergent SESs and LULCC approaches to the study of human-environment interactions can be linked. The quantitative analyses used in LULCC research call for measurable drivers, or mechanisms, while those used to describe change in SESs draw explanations from generalized abstractions. LULC diversity is the proposed link, since it combines a generalized CAS concept with a quantifiable landscape characteristic.

human-environment interactions (the processes) that are encompassed by the SES. That is, the landscape patterns of LULCC are a tangible expression of, and therefore an opportunity to measure, SESs. Integrating the two approaches seems logical. However, for this integration to work, we need to test whether the theory used to describe SESs can be applied with equal validity to LULCC. Certainly, we can apply the metaphors of resilience and sustainability to LULCC: We can evaluate a given landscape to see whether it has retained the same structural (types, number of types and spatial arrangement of types of land-covers) and functional (the goods and services provided by the different land-uses) identity, despite shocks and perturbations such as market crashes, or prolonged drought. But can the CAS characteristics that confer resilience be expressed through LULCC, so that we select appropriate indicators? Can LULCC be explained in terms of a CAS?

Complex Adaptive Systems

Well-articulated theories of complexity have emerged in a range of disciplines over the past century, including in the social, biological and physical sciences (Arthur 1999; Levin 1999; Limburg et al. 2002; Manson 2001; Simon 1962; Werner 1999). At the same time, studies from across these disciplines suggest that a diverse range of systems exhibit similar complex properties (Gunderson and Pritchard Jr 2002; Levin 2003). Importantly, the need to understand and incorporate change and variability has given researchers the impetus to develop the idea of the CAS.

A complex system is one that is “made up of a large number of parts that interact in a non-simple way” (Simon 1962 p. 468). The ‘whole’ that emerges from the interactions of these parts is more than the sum of its parts (Kauffman 1995; Koestler 1968). The definition of a complex adaptive system emphasizes two additional features: diversity, and of course, adaptation. A CAS, according to Levin, is “composed of a heterogeneous assemblage of types, in which structure and functioning emerge from the balance between the constant production of diversity, due to various forces, and the winnowing of that diversity through a selection process mediated by local interactions” (Levin 1999 p. 231). The idea that systems evolve and take on different states is central to the idea of a CAS (Hartvigsen, Kinzig, and Peterson 1998; Holland 1995; Holling, Gunderson, and Peterson 2002; Levin 2003). The ability of a system to adapt is explained by the interactions, or connectivity, between its components. It is also defined by its resilience: its ability to absorb disturbance, self-organize, and persist in the same state over time (Folke et al. 2004; Holling 1973). However, in order to understand and manage for a system’s resilience, one has to understand and be able to describe and measure the characteristics that confer resilience.

CASs theory suggests that diversity/heterogeneity, evolution, aggregation, hierarchy, emergence, localized interactions, connectivity, path-dependency and non-linearity, are all factors that define a system’s structure and functioning, (Arthur 1999; Holland 1995; Kauffman 1995; Lansing 2003; Levin 1998) and hence resilience (Holling 1973). By understanding what these characteristics represent, and the degree to which they are present, we can determine the ability of the system to persist in the face of perturbations.

Diversity or heterogeneity is the most fundamental component of a CAS, because it provides the range of components needed for adaptation (Levin 1999). Diversity means variety, at all levels of organization. Diversity is “neither accidental nor random” (Holland 1995 p. 27). It is dependent on local conditions and interactions such as mutation, recombination, and selection (Levin 1999). These factors, taken in their broader meanings, are the mechanisms that introduce slight variations, and then allow those variations that best suit local conditions to persist. Diversity creates and preserves opportunities for adaptation by providing a range of responses that cover most fluctuations in a system's conditions. The range of responses contributes to the system's resilience (Folke et al. 2004; Holling and Gunderson 2002; Levin 1998).

Certain conditions will favor groups of individual components adapted to them. If conditions change, other groups that did not thrive before now become those best suited to the prevailing environment. The persistence of a given component or group of components is dependent on the context provided by other components within the system (Holland 1995). While some individual components may not persist, the CAS itself does. However, in any CAS some individual components have stronger influences on the system's functioning and identity. Balancing not only the number of types of components, but also the density of each of the components is critical to maintaining the resilience of a CAS.

Evolution is the specific way in which change occurs. Based on the principle of natural selection, evolution draws on the persistence and variability of a system's components. Variability provides the opportunity for new components to develop, while persistence provides the system with continuity (Moran 1979). Change in a CAS is not arbitrary. It occurs as conditions favor the persistence or emergence of certain groups of components over that of others (Levin 1998). These components are then able to replicate and expand, shifting the diversity within the system. Selection for persistence is tightly linked to the size of the pool of component types available, and to the nature or quality of the change (Levin 2003). Evolution is the consequence of adaptation, and provides the mechanism whereby complexity – and hence resilience – are conferred on a system (Holland 1995).

Systems are hierarchical, and can be seen as comprising different levels where components form groups. Aggregation relates to the emergence of system-level patterns resulting from lower level interactions (Holland 1995; Kauffman 1995). Aggregation is defined as the combination of groups of components, that together function as a functional unit at a higher organizational level (Levin 1998). It is through aggregation that hierarchies are created (Ahl and Allen 1996). For example, Koestler's 'holons' are aggregations, where humans are viewed as assemblages of various cell-aggregated organs and society as an assemblage of organ-aggregated humans (Koestler 1968). It is these different levels of 'subassemblies' that add structural complexity to a system (Simon 1962). In the face of perturbation, subassemblies allow parts of the system to persist, and the system can therefore return more quickly to its earlier state or identity. Without these subassemblies, the system would break down into a collection of unrelated components. Reorganization would take much longer, and might lead to the emergence of a different state or identity altogether. When the Khmer Rouge in Cambodia tried to do away with the familiar aggregations of family, neighborhood and village, social order rapidly descended into chaos.

Although the notions of aggregation and hierarchy suggest discrete levels, hierarchical levels are in fact convenient heuristic devices that allow us to represent progression along a continuum (Allen and Starr 1982). It is convenient to examine three points along the continuum that comprises our system of interest. At the top, higher level, units or aggregations are broad and slow moving. They determine the context in which the middle level units operate. The middle level is in turn the context of finer scale, fast moving units. The behavior of fine scale and fast moving units contribute to the identity of the middle level (Allen and Starr 1982). Whereas climate, as a slow broad process determines the average annual precipitation a given location might receive, the actual amount of rain in any given year is determined by daily and monthly variation in seasonal atmospheric circulation patterns. By examining the system at the level above and the level below the level of interest, we have a more complete picture of its structure and functioning (Ahl and Allen 1996).

Localized interactions are the flows that transfer energy and information between the components. These are what make the system dynamic. Interactions between components at the same level are much stronger than those between components at different levels (Simon 1962). The number and type of interactions that flow from one component determine how connected the CAS is. Interactions and flows are the processes contributing to the systems connectivity. Processes that seem to be random at the level of the individual become predictable at the system level (Lansing 2003). Thus, the ways in which the components connect at the local level will determine the identity of the system. The extent to which the system is connected determines the possible alternate states of the system. Connectivity affects the resilience of a CAS by mediating disturbance due to external variability (Holling and Gunderson 2002). Up to a certain point, the greater the degree of connectivity, the more the system is able to withstand external influences. However, systems that become over-connected lose variability and hence adaptability (Low et al. 2003; McClanahan, Polunin, and Done 2002).

If linearity is an outcome equal to the sum of the contributing components, then it is easy to understand non-linearity as an outcome that does not reflect a simple sum of the parts (Holland 1995). Non-linearity in CASs arises because of the way the components of the system interact with each other, creating multiplicative products and not simple summations. As components interact in complex ways, they also adapt and react to the patterns they create (Arthur 1999). They become locked onto a given trajectory or path by feedbacks – the way their behavior influences the system of which they are a part (Figure 2-2). The path is unpredictable because at each point along the trajectory the non-linear interactions have themselves influenced the system. They have created a new, different direction for the path (Arthur 1999; Kauffman 1995; Lansing 2003). The

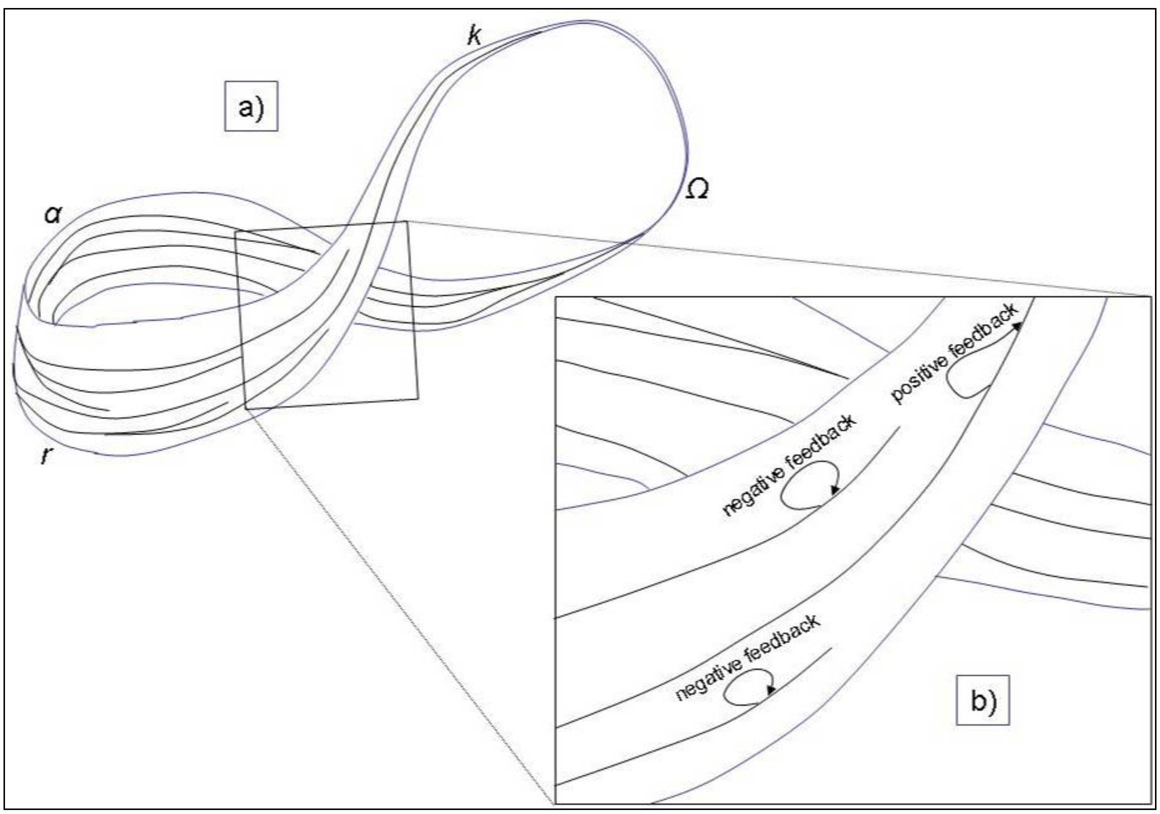

Figure 2-2. Schematic diagram of Holling et al.'s adaptive cycle (2002) showing a) that as the cycle moves from exploitation to conservation phase, it becomes locked onto a single trajectory, as a result of b) negative feedback removing certain paths and positive interactions reinforcing others. The width of cycle "ribbon" indicates the number of potential paths a system can follow.

particular path, with all its variations, defines the identity of the CAS itself. When a system becomes locked onto a given path, it is resistant to modification, increasing system resilience until it reaches a point of criticality (Holland 1995; Levin 1998).

Expressing LULCC in Terms of CAS Concepts

CAS characteristics are already proving useful in case studies evaluating human-environment interactions.[1] For example, they are frequently used to explore SESs qualitatively (Abel and Stepp 2003; Berkes, Colding, and Folke 2003; Berkes and Folke 1998; Davidson-Hunt and Berkes 2003; Janssen 1998; Lansing 2003). Such system-level analyses provide an important compass for regional science because they provide a metaphor for directing ideas. However, as noted above, ways of quantifying social-ecological processes have remained elusive (Carpenter et al. 2001; Chave and Levin 2002; Gibson, Ostrom, and Ahn 2000; Ludwig, Walker, and Holling 2002; Turner et al. 1995). To some extent this issue is worse for large-scale, landscape-level systems because these tend to be even more highly complex and difficult to capture, let alone predict future states for (Cumming and Collier 2005; Gunderson and Pritchard Jr 2002). This has been a contributing reason for why CAS characteristics are not widely used by the LULCC research community, in spite of the early recognition of the complex system nature of LULCC (Turner et al. 1995).

Nevertheless, the CAS characteristics discussed above are readily translatable into concepts already used in LULCC research. Diversity is reflected in landscape heterogeneity. We can assess the landscape in terms of not only the absolute number of types of LULC, but also the prevalence of those LULC types, particularly those that are

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[1] A March 2007 search on Academic Search Premier/EBSCO retrieved more than 300 articles with key words "complexity" and "human-environment interactions".

most critical to sustained functioning of the SES. Spatial metrics of diversity derived by landscape ecologists are already becoming a common feature of LULCC analysis (Lausch and Herzog 2002). The distribution and spatial arrangement of the different LULC types are part of the landscape's diversity. As CAS theory would suggest, the number and relative distribution of LULC types is not arbitrary. We know that "spatial contiguity is the ordering principle for landscapes" (Allen and Hoekstra 1992 p. 47) and that there is spatial autocorrelation in the distribution of components, such as LULC types, across the landscape (Legendre 1993). LULC types, their location and their extent are the result of discernible socio-economic and biophysical conditions and drivers (Wood and Porro 2002).

The view of different socio-economic and bio-physical drivers as selectors of LULC is akin to the notion of evolution. Looking at how LULC changes over time is essentially a description of how a landscape evolves. The evolution of LULC arises out of the persistence and variability of the LULC types within a given landscape. Variability provides the opportunity for new LULC types, while persistence provides the LULC system with continuity. The disappearance of LULC types suggests that they are no longer suited to current conditions within a given SES. The examination of change in LULC over time is an assessment of evolution within the SES. By determining the successional stages of change in LULC diversity, we can describe the nature of that change in terms of emergence, persistence or disappearance of different cover types.

Aggregation, too, is a property of LULCC. We know that the actual interactions are often taking place at the household and land parcel level. It is here that the decision to clear forest patches or plant a particular crop is made. However, at this scale the range of LULC types and their distribution are not easily visible. For LULCC researchers, in their role as external observers, the individual changes occurring at the level of household resource use or small-holder farm activities appear as noise. Patterns emerge at a higher level of aggregation, our level of interest (Ahl and Allen 1996). It is here that we can group the gradations of LULC into classes. These LULC classes reveal the patterns arising from the local-level interactions. They show where, for example, deforestation is concentrated, or how the spatial arrangement of forest loss is related to other landscape features. In turn, our LULC classes are delimited and identified by the broad scale categories to which they contribute. In terms of LULC patterns, these categories appear to be homogeneous and undifferentiated (although still subject to change). For example, much LULCC research examines trends – such as deforestation or desertification – that relate to a single, consolidated LULC type. At this level, where researchers aim to capture a specific process, studies are interested only in general categories of, for example, 'forest' and 'non-forest' (Caldas et al. 2007; Ngigi and Tateishi 2004; Stibig, Beuchle, and Achard 2003; Tansey et al. 2004).

The importance of connectivity in LULCC is shown in the well-documented role of roads as both links and divisions. Roads connect the resources of previously remote areas to markets, and are a key determinant in changing accessibility (Kim, Mizuno, and Kobayashi 2003; Laurance et al. 2002; Nagendra, Southworth, and Tucker 2003; Overmars and Verburg 2005; Southworth and Tucker 2001; Verburg et al. 2002; Xu 2004). However, roads also fragment landscapes and reduce interactions and flows between areas of the same LULC type. Because fragmentation reduces landscape connectivity, it has also received much attention in LULCC research (Hong 1999;

Munroe, Croissant, and York 2005; Nagendra, Munroe, and Southworth 2004). Landscape connectivity controls variability in land-use systems (Bogaert, Farina, and Ceulemans 2005; Burel and Baudry 2005), and therefore influences the resilience of the LULC system. Over-connected LULC systems such as crop monocultures lead to critical dependencies on a narrow range of environmental conditions (Low et al. 2003). Some loosely connected LULC components need to be maintained in order to accommodate change (Pan and Bilsborrow 2005). Other examples of flows are agricultural inputs, such as labor or fertilizer, and financial remittances (Liu 1999; Walker and Soleki 2004). These provide less tangible, but nonetheless real, connections.

Path-dependency in LULCC is created when a certain type of LULC is determined by the previous LULC at that specific location. The non-reversibility of certain LULCC sequences is an obvious example. Forest can be converted directly to grassland, but grassland can only revert to forest if it passes through intermediate stages such as scrub (see for example the decision rules in Verburg et al. 2002). At each successional stage, a new set of LULCC options presents itself. This set of options depends entirely on the circumstances leading to the current LULC. Non-linearities in LULC manifest themselves as the synergistic effects of interacting drivers, which when combined, push a system onto an entirely different trajectory than each of the individual drivers would. For example, the combination of fire suppression and increased grazing in savanna can cause a permanent shift from grassland to woodland (Folke et al. 2004), or the presence of invasive species can alter wet forest recovery after hurricanes (Lugo et al. 2002). This means that the future state of an area of LULC cannot easily be predicted. In a forest, for example, future states may be entirely different, depending on whether it will be steadily thinned, leading first to sparse forest, and then to scrub, or whether it will be clear-cut for grazing or crops.

Importantly, CAS properties are independent of the specific biophysical and socio-economic conditions of different study areas. As such, they give us points of commonality, or generalizations, for cross-site comparison in the study of LULCC. They provide a way to compartmentalize our approach to the complex whole, without favoring one part of the system over another. They also allow us to view LULC abstractly, as a system. As such, because they contribute to structure and functioning, these characteristics can be seen as determining a given LULC system's resilience. By evaluating them, we should be able to assess the ability of that LULC system to persist in the face of perturbations, and whether or not it will continue in a recognizable form for the foreseeable future. Exactly as for any SES, the desirability of a given LULC system persisting will depend on how that system is valued by inhabitants, planners, managers and policy-makers. Strategies that target the mechanisms underlying the CAS characteristics will allow the decision-makers to have greater influence over the ways in which humans influence environmental change.

Clearly, CASs can provide the metaphorical link between LULCC to SESs. While some SESs do not lend themselves completely to spatial, land-based analyses (e.g. fisheries) for the most part the CAS characteristics highlight points of commonality in both research programs. What remains is to detail the way forward from metaphor to measurement (Carpenter et al. 2001). The CASs approach itself is complex, with many identifiers that could be used as a starting point for selecting indicators. However, one characteristic appears to contribute more to the definition of a CAS than any other: *diversity*.

Focus on Diversity

Diversity is a good characteristic for measuring LULCC as a CAS, because it is considered the most fundamental CAS characteristic. Diversity of traits provides the range of components and responses for adaptation (Levin 1999). Because adaptability and adaptation are dependent on variability, diversity determines the potential for change in any system (Levin 1999; Moran 1979). This is true for diversity of languages, organisms, skin color, beak-size, leaf area, and in this case, LULC. For SESs, as with any other system, diversity serves as a buffer to local variation (Low et al. 2003). To give a LULC example, studies show that ecological heterogeneity is closely linked to long-term land-use practices that lead to landscape complexity (Naveh 1994).

As discussed earlier, diversity is not random (Holland 199). It is very much context-dependent. This is important because if we understand the factors affecting diversity, we can predict and plan for desired levels and patterns of that diversity. This serves as a reminder that diversity is inherently neither good nor bad. That kind of subjective evaluation depends on whether or not the observer has an interest in seeing the system maintain its current structure and functioning. In order to fully capture diversity's contribution to a CAS, it is important to think not only as the number of types of components, but also the relative abundance of these types (Magurran 1988). This is because it is the distribution of the total population across the range of types that gives the system its structure (MacArthur 1960).

Diversity is readily quantifiable, and examples from a range of disciplines show not only that measurement is possible, but also that diversity is an important reflection of the state of the system in question. Biodiversity, including species and ecosystem diversity, is perhaps the most well-known (Dauber et al. 2003; Peet 1974), but research in sociology, economics and anthropology shows that livelihood diversity (Kruseman, Ruben, and Tesfay 2006; Perz 2005) and cultural diversity (Maffi 2005; Stepp, Castaneda, and Cervone 2005) are considered successful indicators of global conditions.

To be an effective measurement, LULC must: exhibit itself in terms of diversity, have some order to its arrangement in space and time, and of course, be expressible in quantifiable units. If the LULC of a given area exhibits the property of diversity, we can expect to observe three things. Firstly, and most obviously, that there will be diversity of LULC types, because heterogeneity is the most fundamental property of a CAS (Levin 1999). Secondly, that there will be some order, or non-random pattern to the distribution of LULC types across the landscape, because local interactions between the underlying biophysical and socio-economic conditions are spatially explicit, and will influence what LULC types are able to emerge where (Legendre 1993). Thirdly, we should be able to detect heterogeneity at all spatial scales (Levin 1999). This assumes that the classification system used to determine LULC diversity is an accurate representation of the full range of LULC types in a study area, and an understanding of how – as with other types of diversity (e.g. ecological, linguistic) – the level to which the classification is taken will affect the level of diversity detectable in the landscape, in much the same analysis of linguistic diversity depends on whether one is studying this at the family level (Indo-european) or at the dialect level (Catalan Spanish).

Testing LULC Diversity

There are three main steps to take in order to test whether LULC diversity is a useful way to express change in land-based SESs. To start, we must describe the distribution of LULC diversity across the landscape with concepts of diversity already in use in other disciplines. For example, does LULC richness (the total number of LULC types) vary in a non-random way? Is there variation in the relative abundance of the different LULC types, with some types dominating, and other types being relatively rare? How do the patterns of LULC richness and relative abundance change over space? How do these patterns change at different scales of analysis, from local through to broad scale?

Next, we must interpret LULC diversity in terms of its response to different processes. We should be able to study how areas of differing LULC diversity are related to biophysical and socio-economic factors known to influence LULCC. There are two reasons for doing this: firstly if we understand diversity to be non-random, we must be able to show some causation, and secondly, to support the argument that diversity will allow researchers to compare LULCC in different systems, we must show that the drivers they use to evaluate change affect LULC diversity in similar ways. Finally, we must be able to evaluate *change* in LULC diversity in response to those different processes. Only by measuring how diversity changes over time, and by showing that change as a *response* to different drivers, can we evaluate the extent to which diversity is a measure of the systems adaptive capacity.

Working with drivers that are shown in the literature to be significant factors in LULCC strengthens the chance for results to reflect the validity of diversity as the response variable, and puts the focus on diversity as a response variable, instead of on the drivers as explanatories. LULCC studies have repeatedly identified the following factors as drivers of LULCC: soils, slope, roads, and markets, *inter alia* (Caldas et al. 2007; Arima et al. 2005; Etter et al. 2006; Lambin, Geist, and Lepers 2003; Manson 2005; Mas

Table 2-1. Selected examples of case studies suggesting changes in LULC diversity and underlying factors

Paper	Location	Observed Changes Related to LULC Diversity	Selected Factors
Alados et al. 2004	Spain	Temporal and spatial variation in LULC types	Elevation;, slope; distance from town; population density
Bassett and Zueli 2000	Côte d'Ivoire	Temporal and spatial variation in LULC types	Fire; grazing; rainfall
Bürgi, Hersperger, and Schneeberger 2004	Switzerland	Landscape change and persistence	Topography; distance from centre; accessibility
Caldas et al. 2007	Brazil	Conversion of one LULC type to several others	Soil quality; distance to highway; demographic characteristics; wealth
Chomitz and Gray 1996	Belize	Conversion of one LULC type to several others	Road density; distance from market, soil quality, rainfall
Crews-Meyer 2004	Thailand	Landscape change and persistence, LULC heterogeneity	Elevation; distance from rivers, roads, villages
Cropper, Puri, and Griffiths 2001	Thailand	Conversion of one LULC type to several others	Slope; elevation; protected areas; population density
Douglas 2006	S-E Asia	Land degradation as consequence of new and varied LULC types	Roads; market access; off-farm labor; conflict
Erenstein, Oswald, and Mahaman 2006	West Africa	An agro-ecological gradient of land use, diversity of land use highest at intermediate point on gradient	Distance from urban market
Etter et al. 2006	Colombia	Conversion of one LULC type to several others	Soil; cost-weight distances to roads, rivers, towns; neighboring LULC type
Geoghegan, Wainger, and Bockstael 1997	USA	Assesses *land use* diversity in a study of spatial metrics – diversity as a factor contributing toward land values	Diversity interacting with distance from capital city
Laurance et al. 2002	Brazil	A single LULC type – forest – giving way to several LULC types along gradients of roads and settlements	Population density; road density
Munroe, Southworth, and Tucker 2002	Honduras	Conversion of one LULC type to several others	Distance to roads, towns; slope; elevation
Overmars and Verburg 2005	Philippines	A gradient, with few LULC types at each extreme, and a higher diversity of types in the middle of the gradient	Slope; elevation; distance to: road, market, village, river; population density, ethnicity
Pontius, Shusas, and McEachern 2004	USA	Explores persistence vs. temporal variation in LULC types	n/a
Stefanov and Netzband 2005	USA	Scale dependence, aggregation of LULC types	n/a
Van Gils and Loza Armand Ugon 2006	Bolivia	Conversion of one LULC type to several others	Land tenure; distance from roads, settlements

et al. 2004; Messina et al. 2006; Overmars and Verburg 2005; Soares-Filho et al. 2004; Southworth, Munroe, and Nagendra 2004). In these works, and in others, there is already an indication of how the observed change relates to the number of types, partly because each proximate driver of change referred to represents the introduction of at least one new LULC type. For example, most deforestation studies essentially address the replacement of a single LULC type (forest) with a patchwork of several types, containing remnants of the old-growth forest, cash crops, subsistence crops, pastures, settlements and secondary growth forests (Geist and Lambin 2001; Wood and Porro 2002; Van Gils and Loza Armand Ugon 2006). A list of recent studies, interpreted in terms of change in the number or distribution of LULC types, and the cause of that change, are presented in Table 2-1. While some papers qualitatively discuss proximate drivers and broad mechanisms (Geist and Lambin 2002; Wood and Porro 2002), no cases studies were found that specifically test the scale-dependency of the relationship between LULCC and these factors. These papers provide a list of known drivers influencing LULC diversity, and the nature of the relationships.

Methodology for Evaluating LULC Diversity

The test of whether LULC diversity provides a conceptual abstraction that allows for cross-site comparison, as well as an acceptable measurement of change in complex adaptive SESs has certain key elements. Because individual systems are bounded in space and time, studies must have spatial and temporal extents that are described in terms of the system extents. Studies would need to compare at least two landscapes, to see how LULC diversity is expressed in different SESs. Because systems are multi-scalar, LULC diversity should be evaluated at different spatial scales, in order to identify the effects of scale on diversity responses.

Spatially and Temporally Explicit Studies

Any attempt to quantify change can be done only if appropriate units of analysis are identified. Spatial studies typically use two units, where the unit of interest is the "type" (patch, class or category), and the unit of measurement is a single cell – or pixel – with defined areal extent in a row-column grid. Because geographic studies are often spatially explicit, the effect of location can be taken into consideration. One can treat either patch or pixel as a case, or sample, in a dataset, to which a range of variables can be attributed. Landscape ecology has developed indices of landscape patterns in general and environmental heterogeneity in particular (Gustafson 1998). Indeed, the idea of using LULC types is really no different from the "patch" concept used by landscape ecologists – it simply adds the larger contribution of the socio-economic influence in the definition of landscape patches. Traditionally, landscape patches have referred specifically to ecological systems, but increasingly LULCC researchers have adopted the idea and applied it to units on the landscape that are categorized on the basis of human influence through land use (see for example Southworth et al. 2004). It is important to define the spatial extent or boundary of one's system, so that the distinction between internal variation and external perturbation can be made clear.

Similarly, the temporal grain and extent of the system should be defined. The extent includes both the expected duration of the system, and the total period of the study. The relationship between "lifespan" and study length dictates what one can infer from the changes observed over the study period. The interval for analysis of the dynamics of change must also be defined, and whether the time-step being used captures change represents an actual trend, or simply fluctuations below the level of interest.

Cross-border Studies

Cross-border studies provide an opportunity to explore the differential impacts of the processes behind LULCC (Bürgi, Hersperger, and Schneeberger 2004). By selecting cases with similar biophysical characteristics, they provide research conditions where a range of factors is held constant. This allows other – particularly socio-economic – aspects to stand out. If SESs have experienced different histories, they will have highly dissimilar landscapes, even if their initial biophysical conditions were comparable. Such contrasts provide informative comparisons to the application of the CASs framework.

An ideal situation would be similar-sized, and similarly-formed, islands, or adjacent countries that are separated by a watershed or large river, that have similar biophysical characteristics – at least initially, but which are socio-economically discrete. In such a case, one would seek to emphasize and explore the different social, cultural, political and economic influences on LULC. Alternatively, one could find places that fall under the same socio-economic system, but which cross some kind of bio-physical boundary, such as a mountain range that creates a rain-shadow, or islands belonging to the same nation but which were formed by different processes (e.g. volcanic vs. carbonate platform).

Appropriate Levels and Scales of Analysis

Any case study to test LULCC as a CAS should describe and analyze three levels – the level of interest, and the constraining and contributing levels (Ahl and Allen 1996). The definition of these levels should not be arbitrary, but based on an informed assessment of the spatial and temporal extent of the processes in the system (Figure 2-3). LULCC research generally looks at patterns across large landscapes. Likewise, where it is necessary to represent change across an entire SES, broad or regional-scale studies are the appropriate level to use in capturing social- ecological heterogeneity and dynamics (Turner, Gardner, and O'Neill 2001).

However, the processes underlying landscape patterns range from localized, household-level decisions, to national policy implementation, and from issues of farm-level soil fertility to geologic or climatologic gradients.

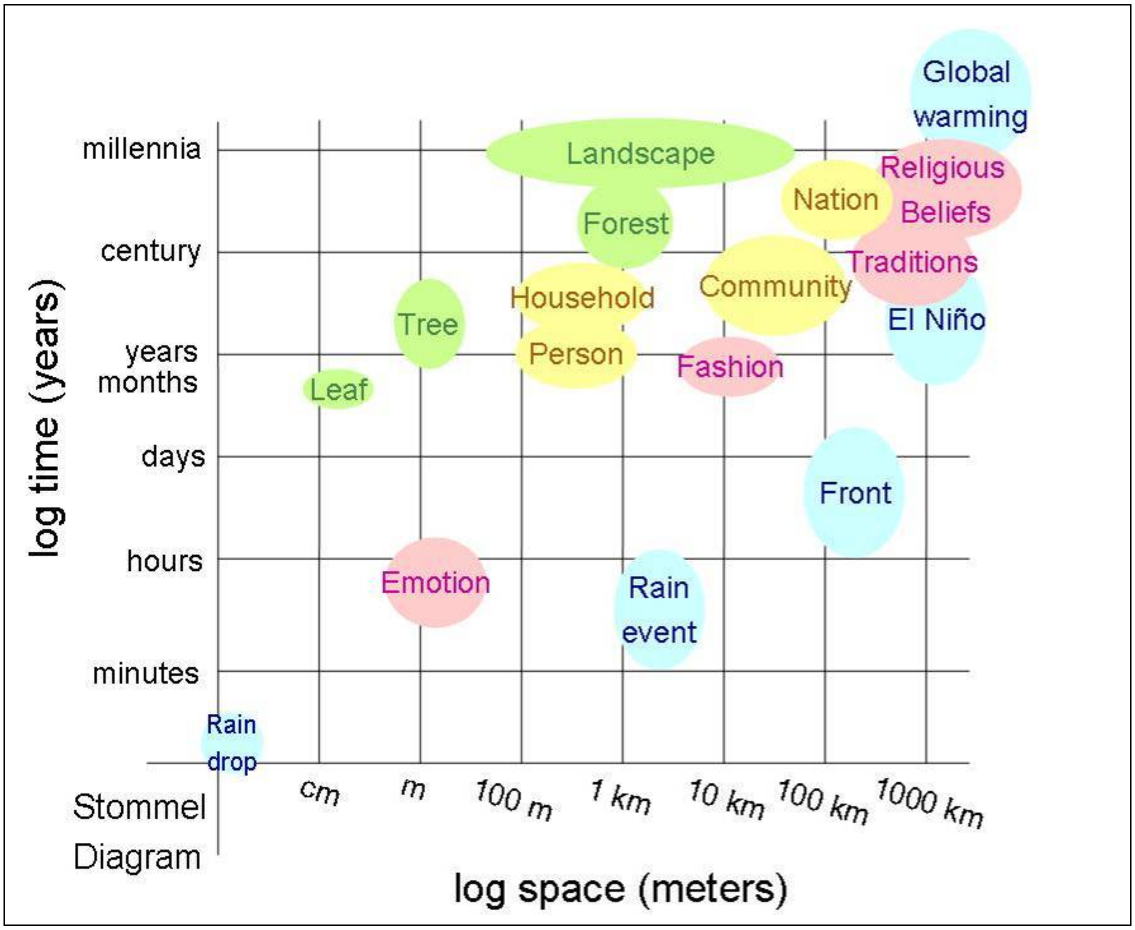


Figure 2-3. Representational diagram showing different temporal and spatial extents of selected SES processes (based on ideas in Holling, Gunderson, and Peterson 2002). Different system types are color-coded as follows: green – ecological, yellow – social, pink – cultural, blue – climatic.

In rural tropical developing countries, the main level of interest would be a meso-level corresponding to the most tangible level of human influence – the community. Contributing to the identity of the community are its constituent members – householders, whose individual choices and decisions combine (at the contributing level) to create the emergent identify of the community. National, provincial and county policies are put into effect at the macro-level and provide the constraining level, or context.

Exploring Patterns of LULC Diversity and its Response to Factors Influencing Change

LULC diversity offers not only a point of comparison between different landscapes. It also can be used to compare the same landscape at different moments in time, or at different scales of analysis. For example, the frequency distribution of the variety and relative abundance of LULC types at 3 scales, will differ significantly from each other (item i in Table 2-2, Figure 2-4-a). At all three scales, the frequency distribution of LULC diversity (both variety and relative abundance) differ from a homogeneous distribution of a single LULC type, and a completely random distribution of the maximum number of types (ii in Table 2-2, Figure 2-4Figure-b, -c, and -d).

At the micro-scale, where mechanistic interactions are taking place, at any one location individual agents will be able to select for only a few types of LULC from the large range of LULC types. This means that though the individual types might vary between locations, at the micro-scale low magnitudes of LULC diversity will dominate (iii in Table 2-2, Figure2-4-b). At the meso-scale, which reflects the level of interest, intermediate levels of diversity will dominate (iii in Table 2-2, Figure 2-4-c). The collective selections resulting from the human-environment interactions occurring at the level below will produce a wide range of LULC types across the entire study area. This means that higher magnitudes of diversity will be present in some locations, but not others, as the presence of some types will be constrained in other locations by socio-economic and environmental factors. The broad macro-scale represents the context, and as such contains the full range of LULC types. At this scale, high magnitudes of LULC variety will dominate, although there will still be spatial variation in LULC relative abundance (iii in Table 2-2, Figure 2-4-d).

While the list of factors that could potentially influence LULC diversity is long, only a few key ones are selected here. As noted above, these have been chosen because they are known to affect LULCC (see Table 2-1). This is done to shift the emphasis from what is causing change, to how the system is responding to change. Since the understanding of the effect of these factors is known for individual LULC types, the response of LULC diversity can be better interpreted. The patterns of LULC diversity relating to key biophysical and socio-economic factors, such as slope, soil, distance to roads, and distance to market, can then be evaluated.

LULC diversity will be relatively low where slope is low, increasing initially as slope increases, until reaching a point of steepness where LULC diversity will drop to very low magnitudes (iv in Table 2-2, Figure 2-4-e). High LULC diversity will be associated with soil types with intermediate levels of fertility, and with good drainage, as many different kinds of LULC will be possible. Lower magnitudes of LULC diversity will be found on nutrient poor soil types, and on very clayey soils because only a few uses will be possible, as well as on soil types that are extremely fertile because high-value crops might be the most profitable use (v in Table 2-2, Figure 2-4-f). Soil quality will be strongly associated with slope, and the interaction of these variables will need to be controlled for.

High LULC diversity is correlated with an intermediate distance from road (Nagendra, Southworth, and Tucker 2003). Close to roads, a few types will dominate, with diversity increasing sharply within accessible distance from the road, and then decreasing steadily as limited access reduces human influence on the landscape (vii in Table 2-2, Figure 2-5-g). A similarly ordered relationship, but with different intensity of relationship, will exist between LULC diversity and distance to market (vii in Table 2-2, Figure 2-5-h). Closer to the market, diversity will be low, as only LULC types reflecting goods that can be traded on the open market will be present. At some intermediate distance, as returns for effort become marginal, LULC diversity will be highest, as types dominated by humans are interspersed with those with little human influence. Importantly, most access to markets is along roads, and some considerations should be given to testing LULC diversity against cost-weighted distance to market surfaces.

The magnitudes of LULC diversity across a social-ecological landscape are constantly subjected to forces of change as that landscape dynamically adapts to on-going human-environment interactions. At the same time, the magnitude of LULC diversity at any one point in time will affect the potential magnitude in the future. By creating a sequential set of successional states, a trajectory of change in LULC diversity for any location can be evaluated.[2] Certain trajectories of LULC diversity magnitudes will dominate in a given landscape. This allows for an assessment of what magnitudes of LULC diversity persist over time, as well as providing information on where, and between which time-steps, the greatest change in the magnitude of LULC diversity has taken place. The long term trend will be towards intermediate magnitudes of LULC diversity at all scales (viii in Table 2-2, Figure 2-5-i). At the meso-scale level of interest, fluctuations can be expected in response to variability in drivers operating at this scale, such as inter-annual variability in rainfall, or volatile market conditions. At the fine-scale, a gradual increase in the magnitude of LULC diversity will occur, as humans introduce a larger range of LULC types into areas previously beyond their immediate influence, while at the broad-scale, there will be a gradual decline as certain favored LULC types begin to dominate the landscape. The occurrence of a given magnitude of LULC diversity at any location is not random, but depends on the preceding magnitude at that location. In addition, certain trajectories of change will dominate because some LULC types are converted more easily (Verburg et al. 2002). Certain trajectories of change in diversity magnitude are more likely to occur than others,

[2] In LULCC studies, the term ‘trajectory’ refers to a category of change that groups together all areas that have the same specific LULC conditions at each of a series of time-steps. In terms of actual types an example would be forest-woodland-pasture-crop, and in terms of number of LULC types, 2-2-3-9, reflecting increasing LULC variety.

and only a few of the potential trajectories will cover extensive areas. There are many potential LULC trajectories that will not happen (e.g. forest to city to forest to city across four 5-year time-steps), and likewise, there are many diversity trajectories that are unlikely (e.g. 10-1-10-1 in a place with a maximum of 10 LULC types). As scale increases, so too does the overall magnitude of diversity, since more types of LULC will be found as the area of analysis increases. This increase in magnitude means that the range of LULC variety levels increases, thereby increasing the number of both potential trajectories and those covering extensive areas on the landscape (viii in Table 2-2, Figure 2-5-j). In addition, the spatial extent of a given trajectory is dependent on the initial extent of its initial class.

Just as there is continual variation in magnitude of LULC diversity, some of the factors influencing LULC diversity themselves are undergoing change at clearly discernible rates. This means that the relationship between LULC diversity and these factors will change over time, and that this change provides important information on the state of the SES. Other factors, however, remain effectively constant. Over time, the threshold for a decrease in LULC diversity will become associated with steeper slopes, while at the same time LULC diversity in flatter areas will decrease (ix in Table 2-2, Figure 2-5-k). As demand for agricultural land increases, areas that are flatter lose LULC diversity as agriculture replaces other, less human-dominated, cover types.

Initially, there may be some increased heterogeneity, but ultimately all land tends towards conversion to the LULC represented by the dominant crop (Soini 2005). Similarly, over time the mean magnitude, as well as the variance, of LULC diversity will increase on certain soil types, but not necessarily all (x in Table 2-2, Figure 2-5 -l). Over time, LULC diversity will decrease closer to the road, while higher magnitudes of diversity will be found further and further away

Table 2-2. Quantifiable aspects of LULC diversity, indicating hypothesized responses

	Measurable Response	Predicted Response Attributes	Diagram in 2-4 to 2-6
i	Magnitude of LULC diversity	Scale dependent	a)
ii	Magnitude of real-world LULC diversity compared to null and random models	A null model of one type would have no diversity, whereas a random model would represent all magnitudes of diversity equally. Actual LULC diversity would have measurable mean and variance.	b), c), d)
iii	Magnitude of LULC diversity	Distinct distribution patterns, peaking at intermediate magnitudes which vary according to scale	b), c), d)
iv	Interaction of LULC diversity and slope	3^{rd} order polynomial relationship	e)
v	Interaction of LULC diversity and soil type	Difference in range and mean magnitude of diversity according to soil type / fertility	f)
vii	Interaction of LULC diversity and distance to roads, distance to market	2^{nd} order polynomial relationship	g), h)
viii	Change over time in magnitude of LULC diversity	Scale dependent, but at all scales a tendency towards intermediate magnitudes of diversity persisting	i), j)
ix	Change over time in relationship between LULC diversity and slope	A weakening relationship at later points in time, with peak magnitudes of diversity associated with increasingly steep slopes	k)
x	Differential changes over time in magnitudes of LULC diversity on different soil types	Initially, increasing differences in mean magnitudes of LULC diversity, until demand for land is high. Then, increasing magnitudes of diversity on poorer soil types.	l)
xi	Change over time in magnitude of LULC diversity with changes in distance to roads	A weakening relationship at later points in time, with peak magnitudes of diversity associated with increasingly greater distances to roads	m)
xii	Change over time in magnitude of LULC diversity with changes in distance to market	Strong relationship maintained, but peak magnitudes of diversity associated with shorter distances to market	n)

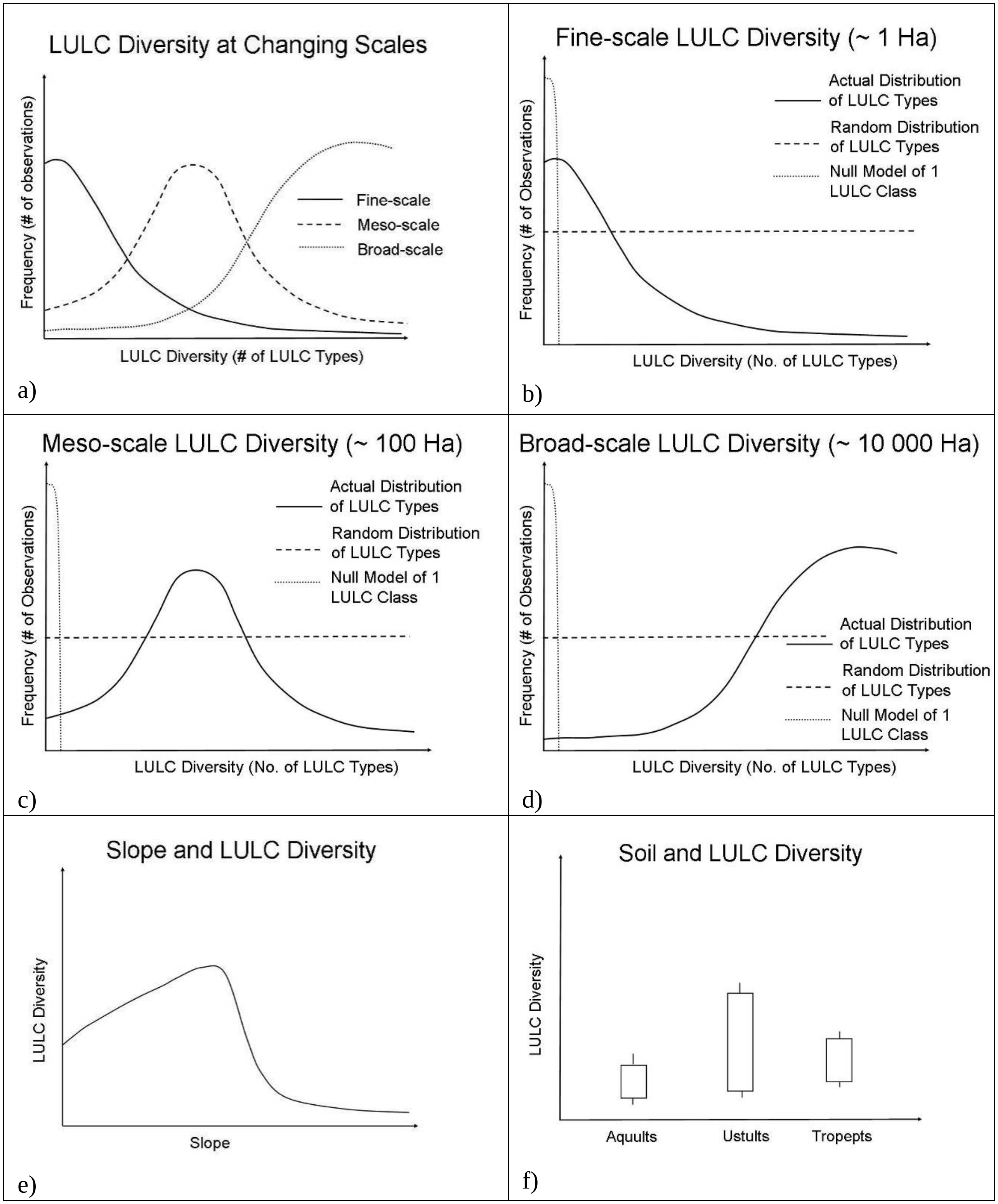


Figure 2-4. Schematic diagrams representing a) - d) the distribution of LULC diversity at different scales, and e) – f) the interaction of LULC diversity with slope and soil

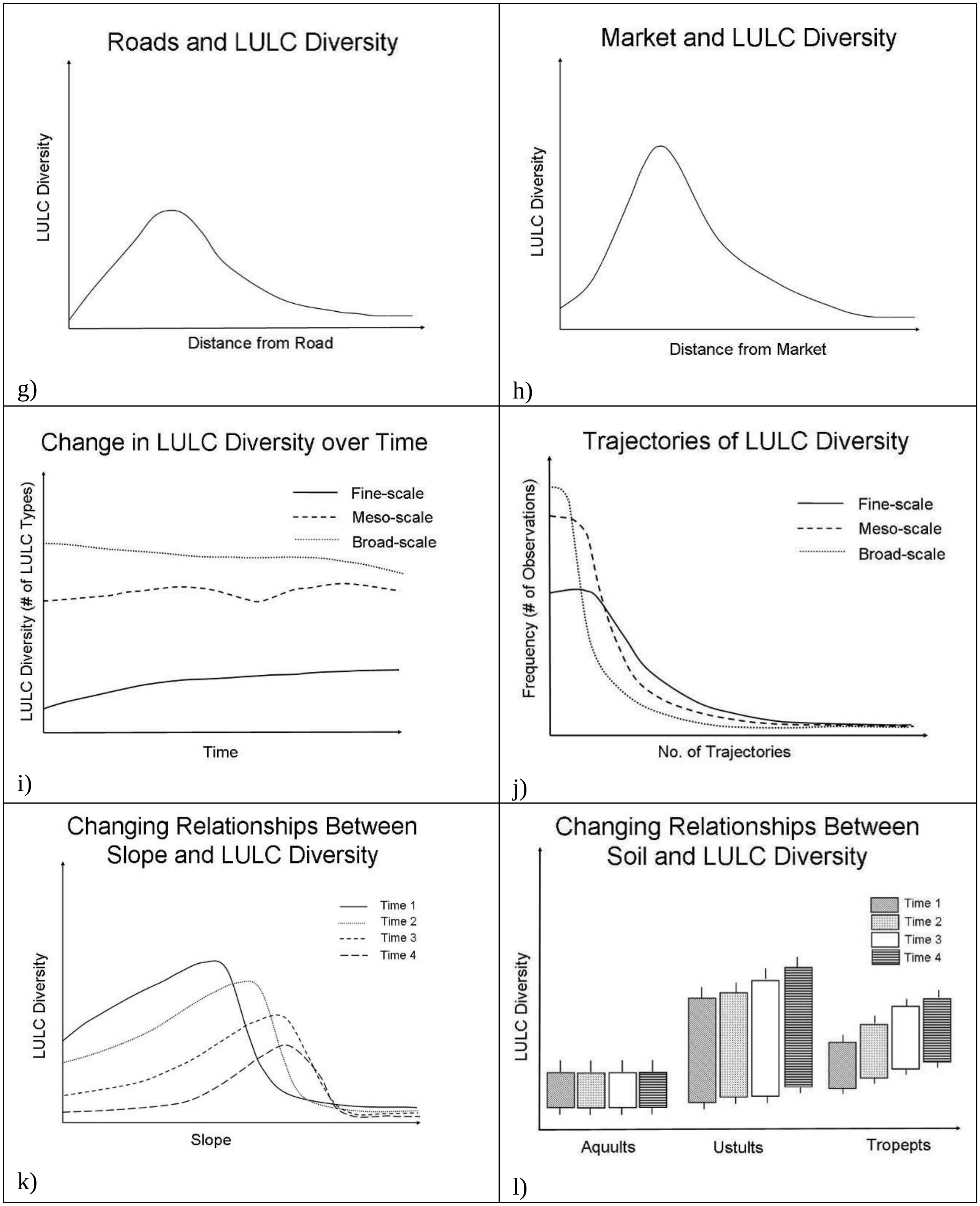
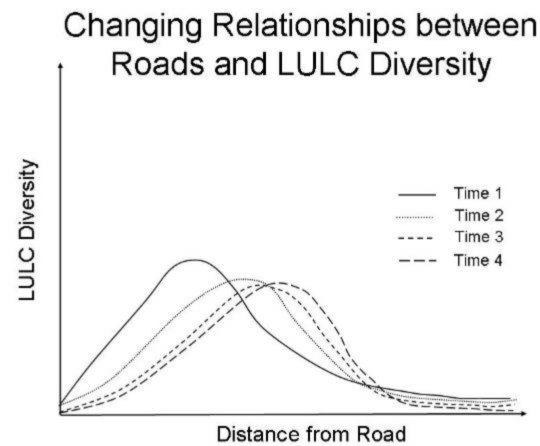
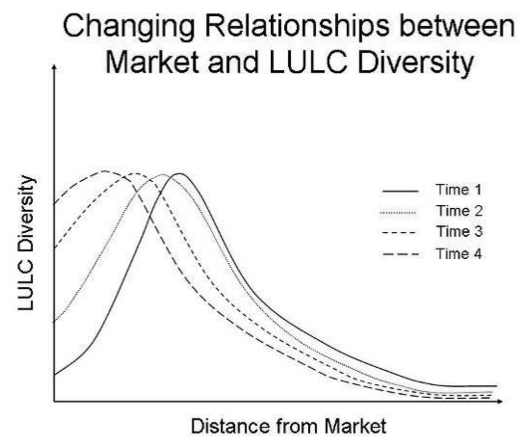


Figure 2-5. Schematic diagrams representing g) – h) the interaction of LULC diversity with distance from roads and market, i) – j) changes in LULC diversity over time, and k) – l) changes in the relationships between LULC diversity and slope and soil.



m)



n)

Figure 2-6. Schematic diagrams representing m) – n) changes in the relationships between LULC diversity and distance from roads and market.

(xi in Table 2-2, Figure 2-6-m). With increasing demand for land, the conversion of LULC to agriculture will occur further and further from the road, pushing areas of high LULC diversity further away. In highly connected SESs with dense road networks, the relationship between LULC diversity and distance from roads becomes weak. These trends will be different for the changing relationships with distance to market. Over the trajectory period, LULC specialization in response to economic forces will lead to increasing LULC diversity closer to markets, while lower magnitudes of LULC diversity will still be found further and further away (xii in Table 2-2, Figure 2-6-n).

A Preliminary Assessment of the LULC Diversity Concept

The village of Trapeang Prasat lies in the hilly east of Ordar Mean Chey province in northern Cambodia (Figure 2-7). It is a frontier town that has experienced rapid change since the end of fighting between the Khmer Rouge guerrillas and the Vietnamese-backed government in the early 1990’s (Gottesman 2004). In the ensuing years it has grown rapidly, and with this growth, its forested areas have given away to a range of different human-dominated LULC types.

According to the hypotheses in Table 2-2, we should be able to see detectable patterns of LULC diversity distributed across the landscape. This distribution would differ significantly from the LULC diversity of a null model of total randomness, which would comprise a landscape containing all the potential magnitudes of LULC diversity, distributed randomly across the landscape (Figure 2-4a). The distribution would also differ from LULC diversity calculated on a null model of total homogeneity, which would consist of a landscape containing only one LULC type – that is, all pixels in the landscape will carry the same value. According to the hypotheses, LULC diversity at different scales would reveal different patterns on the landscape. Close to the roads leading to Trapeang Prasat, as well as close to the town itself (where the market is located at the intersection of the two roads) diversity should be higher, decreasing further and further

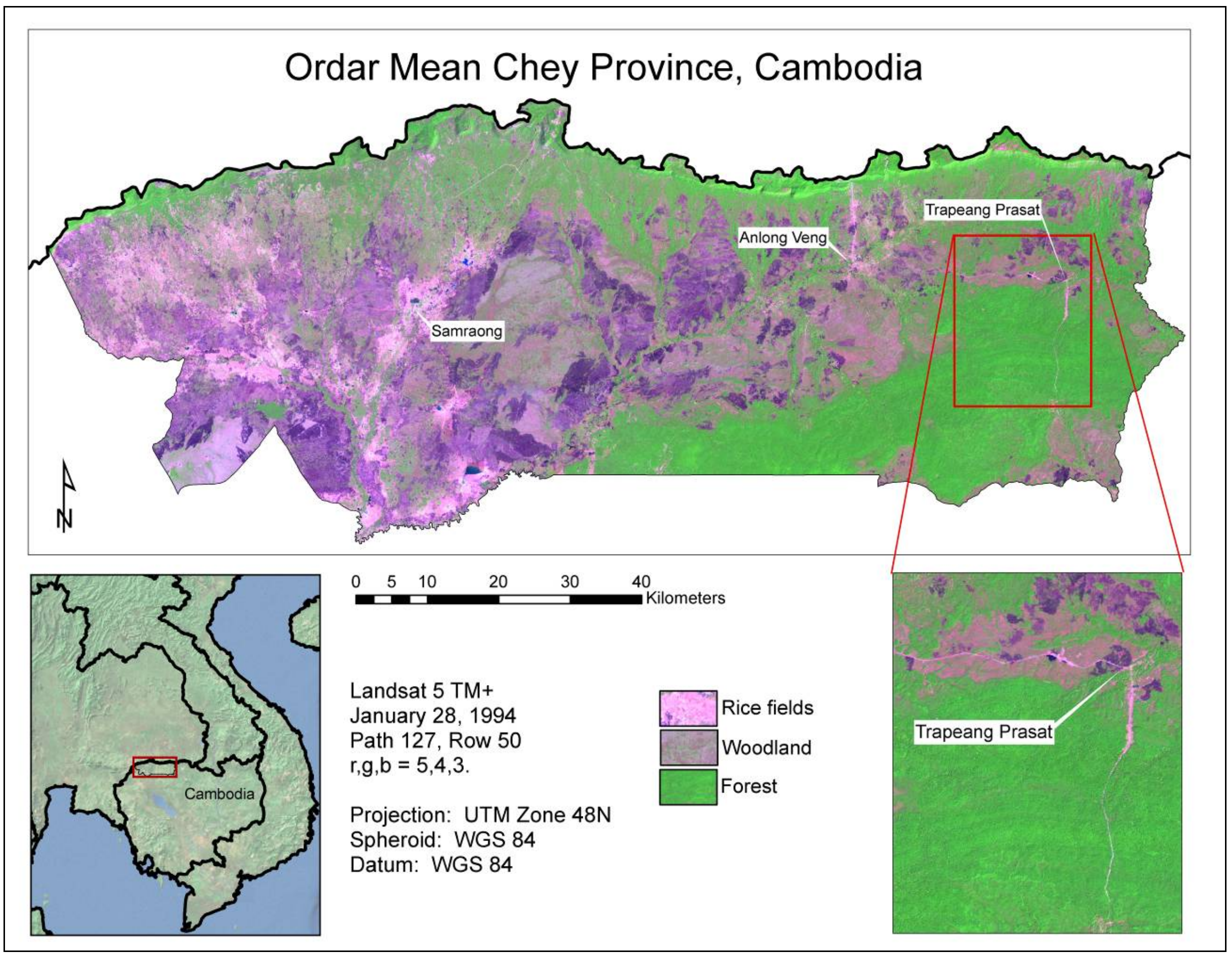


Figure 2-7. Location of Trapeang Prasat village in northern Cambodia.

away from these features. As one moves south into the elevated area to the south of Trapeang Prasat, LULC diversity should decrease (Table 2-2).

A 12-class classification map of the 30 m resolution subset of the satellite image shown in Figure 2-7 was created to assess the distribution of LULC diversity in the landscape surrounding Trapeang Prasat (Figure 2-8a). Two different moving window sizes (3x3 pixels and 33x33 pixels) were run across the classified raster to measure LULC diversity (as a simple measure of variety of LULC types) at a micro-scale of around 1 ha and a meso-scale of about 100 ha (Figure

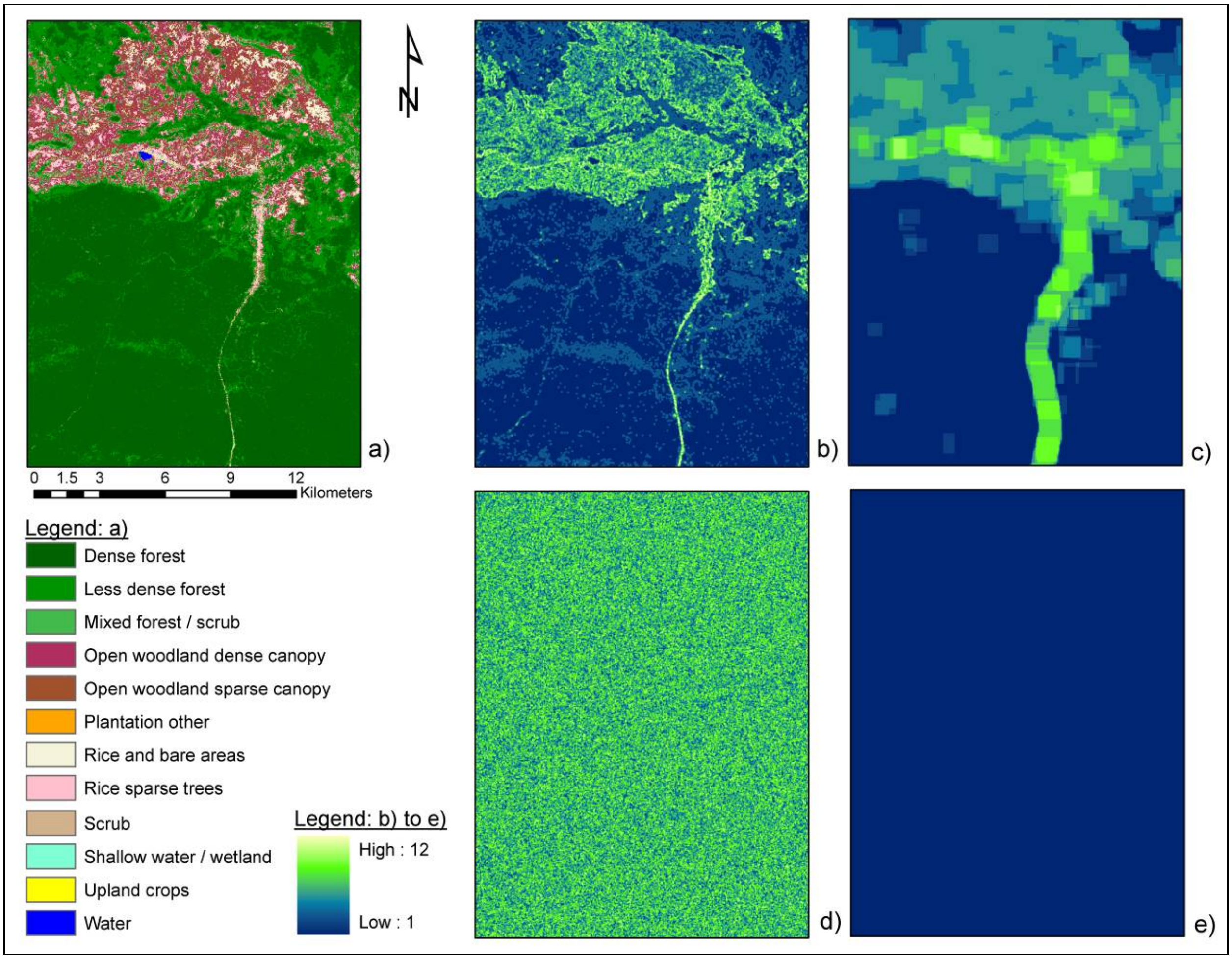


Figure 2-8. A test of LULC diversity on a) the 12-class classification of the Trapeang Prasat area, showing b) micro-scale diversity and c) meso-scale diversity.   Micro-scale diversity of a random landscape is shown in d) while that of a completely homogeneous landscape is shown in e).

2-8b and Figure 2-8c). A 3x3 pixel moving window was then run across the random landscape and the homogeneous landscape (Figure 2-8d and Figure 2-8e).

As Figure 2-8 shows, the actual distribution of LULC diversity differs considerably from the random and homogeneous null models, and shows the key landscape features visible in the classification. At the micro-scale (Figure 2-8b) the patterns closely mirror those of the actual classification, but it the magnitudes of diversity at this scale are quite fragmented, so that the matrix of crop and woodland visible in a) begins to look almost random. At the meso-scale in c) key processes are emphasized, so that the roads and village node stand out clearly as areas of high diversity. The undisturbed forest on the hills to the south of Trapeang Prasat appears as an area of low LULC diversity, while the matrix of crops and woodland show intermediate magnitudes of diversity. The landscape is now generalized and represented as quantitative integer data.

The frequency distribution for LULC diversity shows the expected left-skewed shape (Figure 2-9) and resembles the hypothesized distribution curve, and differs from the two null models. Since the data are quantitative, we can calculate means and standard deviations for the landscape. The micro-scale has a low mean magnitude of LULC diversity (1.97 types), with a standard deviation of 1.15, while the meso-scale's mean is 5.28 with a standard deviation of 3.11. This difference is that anticipated by the shift along the x-axis anticipated by the hypothesized distribution in Figure 2-4c. With these measures alone, it is clear that to contrast with other landscapes – even, for example, to the west of the same province in Ordar Mean Chey, there would be distinct commonalities, but also differences relating to the extent of human influence on the landscape.

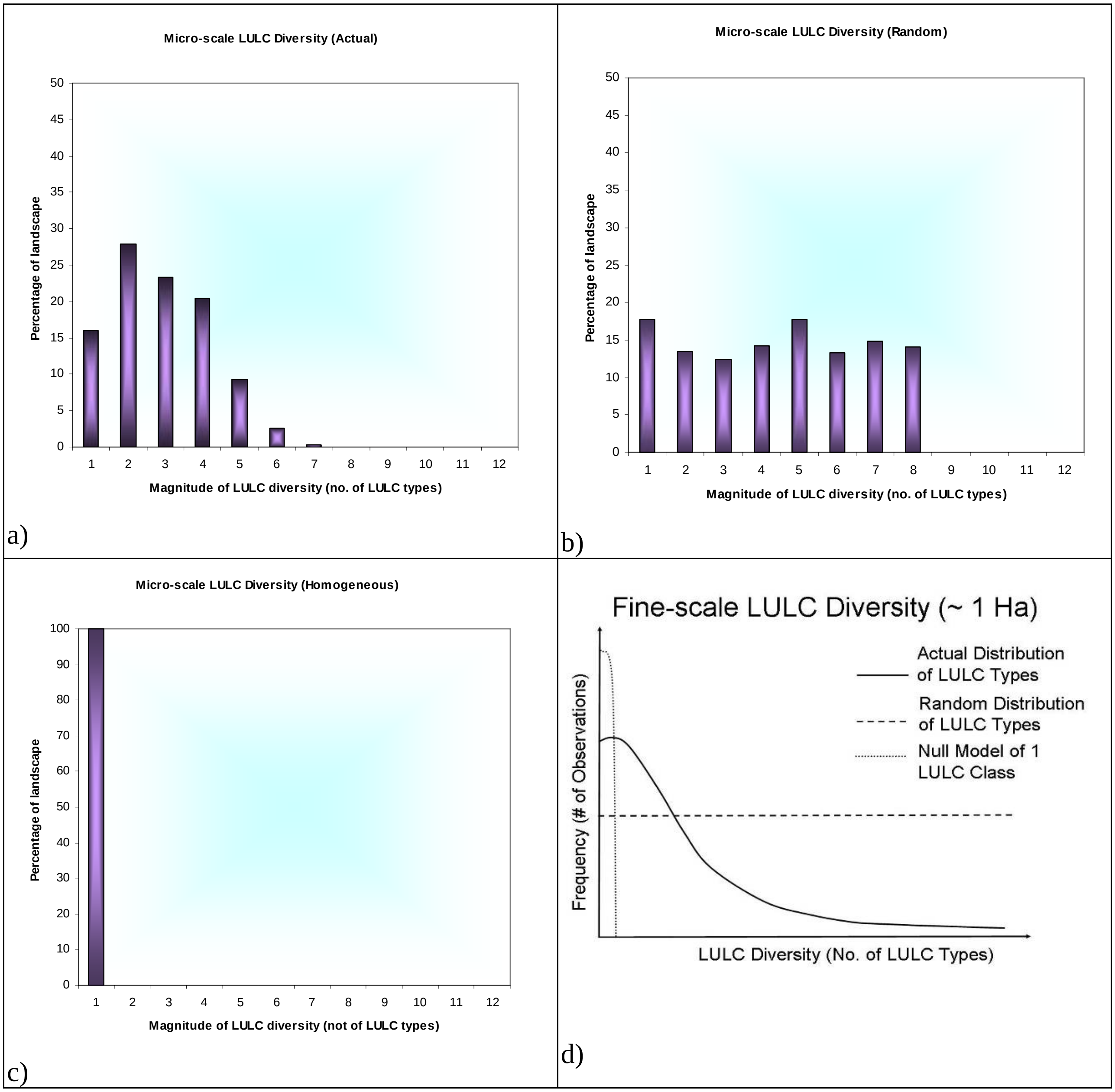


Figure 2-9. Comparison of a) actual LULC diversity to null models of b) random diversity and c) a homogeneous landscape.

Conclusions

At the same time as researchers have begun to embrace the dynamic and multi-scalar nature of the world (Folke et al. 2002; Holling 2001; Lambin, Geist, and Lepers 2003; Munroe, Southworth, and Tucker 2004; Young et al. 2006), the uncertainties and complexities that abound in human-environment interactions present distinct challenges to both land-use land-cover change (LULCC) and social-ecological systems (SESs) research. Because of the unique combinations of landscape characteristics, land change scientists have struggled to find sufficient generalizations that allow them to theorize beyond immediate case studies, hindering their ability to extrapolate and predict using a hypothetico-deductive approach (Briassoulis 2000; Bürgi, Hersperger, and Schneeberger 2004; Perz 2007; Rindfuss et al. 2004). For SESs researchers, on the other hand, the difficulty has been to identify ways to evaluate system change quantitatively (Carpenter et al. 2001; Cumming et al. 2005).

The theoretical framework and methodological approach outlined here explores both the usefulness, and the feasibility, of explicitly linking LULCC and SESs research. By using the CASs paradigm, we can allow the strengths of each research program to fill in gaps in the other. Firstly, the CASs theoretical framework generally, and the concept of diversity in particular, provides researchers with measurable points for comparison, extrapolation and prediction. For researchers focusing on LULCC, a CASs approach should lead to more coherent and systematic analyses that are not context-specific or discipline-dependent (Perz 2007). LULC diversity can be tested and evaluated in any landscape, independent of the prevailing environmental and social characteristics. As such, CASs theory allows LULCC research to move from inductive towards deductive analysis, by providing the theoretical basis from which to posit predictive hypotheses. Trends in magnitudes of diversity can be inferred, based on the CASs ideas of selection, emergent properties, non-linearity, path dependency and scale, inter alia (Ahl and Allen 1996; Arthur 1999; Holland 1995; Kauffman 1995; Lansing 2003; Levin 1998).

Secondly, by explicitly treating LULCC as the expression of the various components of a SES, CASs theory provides the opportunity to measure that system's processes. Quantifying a system's resilience has to date largely been an elusive target, with implications for effective management. This framework suggests that in order to assess the likelihood of a system changing or persisting in a given form, one needs to work with the properties that confer resilience. Conceptually, evaluating change in LULC diversity does precisely that, since any change in the range of potential responses will affect the ability of a system to adapt and persist (Holland 1995; Levin 2003). By using LULC as an indicator, we can now spatially represent change in the condition or state of different SESs.

The focus on diversity as opposed to specific LULC types provides a generalized unit of measurement that can be tested and compared in disparate SESs, whose diversity is built of different sets of LULC types. Even where systems might have different magnitudes of LULC diversity, drivers of change are still likely to cause similar response patterns, due to the ongoing selection process and its interplay with size of the pool of components. For example, the magnitude of diversity in a given landscape will have a non-linear response to the development of a new road, or the opening of a new market, with magnitudes of diversity increasing up to some intermediate distance, and then decreasing again.   The nature of the relationship should hold constant for different systems, even though the exact coefficients representing that relationship might vary, allowing for extrapolation and prediction. Yet it is precisely the difference in those coefficients that provides with a meaningful measure of how each system is faring relative to the other.

Analysis at multiple scales is important, as LULC diversity patterns will respond to different factors at different scales. For example, different broad-scale factors such as national policies and climatic conditions provide the context that determines the maximum magnitude of diversity. Likewise, variation in soil type or quality at the local level will influence both the type and range of different LULC types, leading to different magnitudes of diversity emerging at the level of interest.

Because they are complex and adaptive, SESs are constantly changing. If we conduct analyses across multiple points in time, we can predict that changes (or not) in LULC diversity will reveal where the SES identity is changing or persisting in terms of its structure and function. Over time, we can expect to see a trend towards intermediate magnitudes of diversity in response to local human-environment interactions (Levin 1999). For example, places with low LULC diversity will experience the emergence of higher magnitudes as people convert land in undeveloped areas, or develop specialty activities to meet market niches in over-simplified systems. In areas with very high LULC diversity, market forces will favor some activities over others, leading to a selection process that reduces magnitudes somewhat.

The holistic approach provided by CASs analysis can accommodate the range of social and environmental facets of LULCC change, and deal with contrasting cross-site comparisons. As such it should prove useful to researchers trying to develop LULCC research as a science (Rindfuss et al. 2004; Walker 2004a). Because LULC is spatially and temporally explicit, it should be useful to consider it as the physical manifestation of an underlying SES, thus providing an opportunity for SESs research to progress from using CASs mainly as a qualitative evaluation to using it for quantitative assessments. By framing human-environment interactions as CASs, we can link the patterns of LULCC to the processes of SESs, and so quantify change and resilience across different landscapes.

CHAPTER 3
PATTERNS OF LAND-USE LAND-COVER DIVERSITY IN SISAKET, THAILAND AND ORDAR MEAN CHEY, CAMBODIA

Introduction

The full development of a science or discipline requires both strong theoretical foundations and empirical measurements. Land-use land-cover change (LULCC) researchers are seeking theoretical generalizations that would increase their ability to compare different regions and contexts (Perz 2007, Rindfuss et al. 2004). The complex nature of the social and ecological interactions underlying LULCC is a challenge to the development of a deductive research approach (Bürgi, Hersperger, and Schneeberger 2004). The variability and complexity of local-level interactions have confounded researchers' ability to predict accurately the extent, nature and even direction of change beyond the immediate location being studied. Theoretical frameworks currently used to guide the relatively young LULCC research program tend to have a one-sided focus that depends on the disciplinary origin of the researcher (Irwin and Geoghegan 2001; Walker 2004). Consequently researchers have yet to advance LULCC studies to a point where existing theories can be tested under a range of conditions. This paper tests the application of the theory of complex adaptive systems (CASs) generally, and the concept of diversity specifically, to the study of land-use and land-cover (LULC), as a way of generalizing landscapes (so that they are describable without reference to specific LULC types) to allow prediction and cross-site comparison (as detailed in Chapter 2).

Increasingly, researchers are aware of the need for an integrated and interdisciplinary approach that incorporates ecological, social and economic sciences (Holling, Gunderson, and Ludwig 2002). There is also a growing body of research treating the human-environment interactions that underpin LULCC as social-ecological systems (SESs) (Berkes and Folke 1998; Janssen, Anderies, and Ostrom 2007; Redman, Grove, and Kuby 2004). SES research builds on the understanding of human-dominated systems as being complex, diverse, multi-scalar, non-linear and self-organizing – that is, as CASs (Cumming and Collier 2005; Holling and Gunderson 2002; Janssen, Anderies, and Ostrom 2007; Levin 2003; Odum 1975). Since LULCC and SESs are both examinations of human-environment interactions at the landscape level, their research programs can be seen as complementary. LULCC addresses the spatial pattern, while SESs treat the process, behind these interactions. As such, LULCC is a tangible expression of SESs (as detailed in Chapter 2). Because CASs theory has been used successfully to give qualitative and quantitative evaluations of disparate SESs (Berkes, Colding, and Folke 2003), we propose that by framing LULCC as the manifestation of the activities of a SES, we should be able to evaluate different landscapes in terms of SESs, to see how changes in the structure and functioning of generalized SES characteristics, such as diversity and emergent properties, respond to the processes already known to affect LULCC. A CAS approach should allow researchers to target the very complexity of human-environment interactions that has hampered the ability of researchers of LULCC to move beyond context-specificity, while simultaneously providing the means for SESs researchers to quantify processes underpinning SESs.

LULC Diversity

Diversity is one of the most fundamental CAS characteristic – in any system (Holland 1995; Levin 1999). It provides the range of components which form the basis for the responses that lead to adaptation. The concept of diversity is familiar, and has been applied widely, from cultural anthropology to livelihood systems, sociology, economics and ecology (Dauber et al. 2003; Kruseman, Ruben, and Tesfay 2006; Maffi 2005; Peet 1974; Perz 2005; Stepp, Castaneda, and Cervone 2005). Diversity is also measurable, which means that it can be quantified and evaluated for any dynamic system. It can therefore provide a point of comparison between systems with dissimilar states of structure and functioning. As such, it is a good characteristic for testing the applicability of CASs theory to LULCC, while also being informative as a standalone concept.

The spatial analysis of diversity is not new; landscape ecologists regularly use diversity metrics to analyze ecological change at broad scales (Lausch and Herzog 2002). It is a small step from the way landscape ecologists divide their landscapes into ecosystems, to the categories of LULC where land-change scientists add the human dimension. For this reason, we move beyond analyses of individual LULC types to looking at the whole landscape and examining all the types together. Landscapes can be evaluated both in terms of the absolute number of LULC types, as well as the extent to which LULC types are sustained, especially dominant types or those that underpin the functioning of the SES. A focus on the diversity of LULC types, will allow studies to be independent of the actual nature of the LULC categories themselves, and so allow for extrapolation and prediction (as detailed in Chapter 2).

Broad Research Goal

This paper is part of a broader program developing CASs approaches for linking LULCC analyses to SESs as a way of quantifying generalized processes (as detailed in Chapter 2). This entails combining CASs – the framework used by the SESs research program to describe process — with the spatially explicit methods used in LULCC research to measure pattern (Figure 3-1). The assumption that LULC represents a tangible expression of the components of a SES allows the strength of each research program to fill the gap of the other.

If we want to use LULC to represent the components of a SES, we need to be able to identify the range of LULC types in a landscape and we would need to be able to detect different LULC patterns at different scales. If we express these patterns through a CAS framework, we should be able to use LULC diversity responses to various drivers of change as a way of studying a given social-ecological landscape in terms of its connectedness, dynamism, stability and likelihood of persistence.

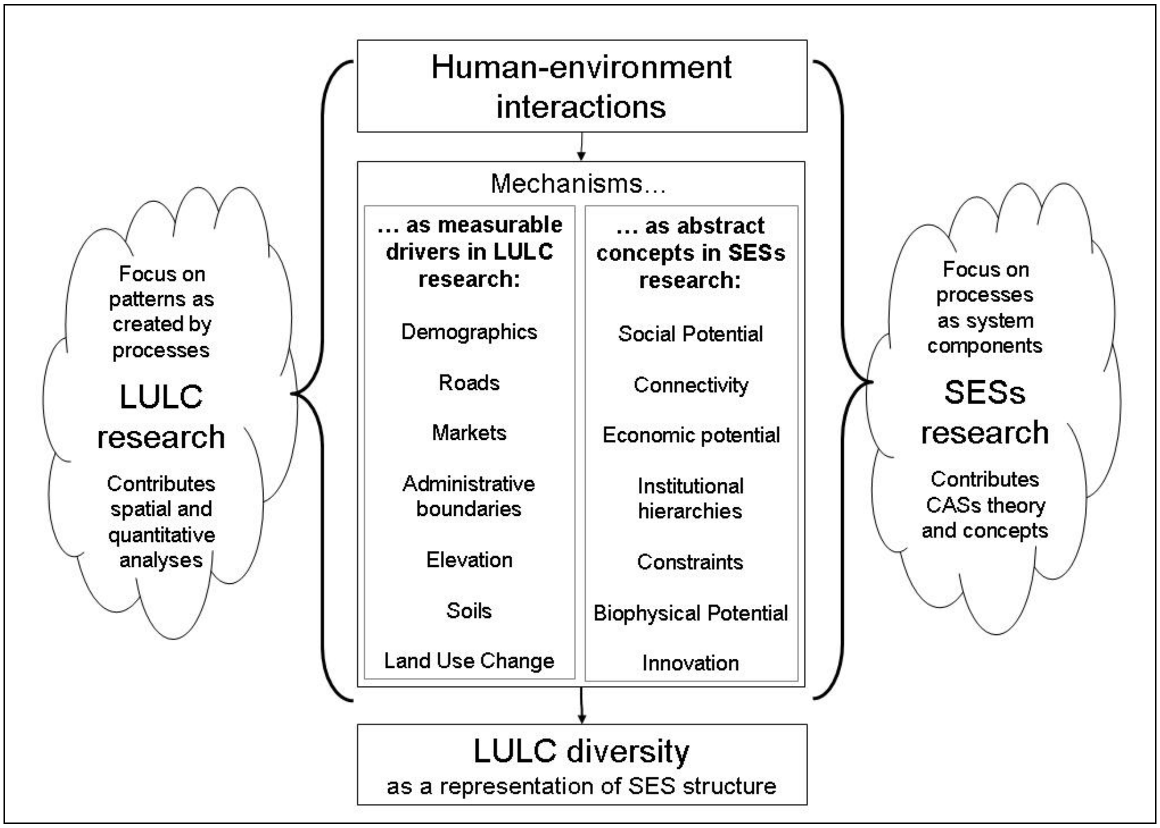


Figure 3-1. Schematic diagram showing how the divergent SESs and LULCC approaches to the study of human-environment interactions can be linked. The quantitative analyses used in LULCC research call for measurable drivers, or mechanisms, while those used to describe change in SESs draw explanations from generalized abstractions. LULC diversity is the proposed link, since it combines a generalized CAS concept with a quantifiable landscape characteristic.

Specific Research Objective

In this paper, we focus on diversity as a key CAS concept and as the main characteristic that underpins the complexity of human-environment interactions central to both the LULCC and SESs research programs. In order to test LULC diversity as a unifying, non-ecosystem specific characteristic for cross-site comparison, we need to show it as non-random, presenting distinct patterns on the landscape at different scales, with different magnitudes of diversity dominating at different locations, and with meaningful variation in magnitudes of diversity over time (as detailed in Chapter 2). We use the following questions to guide our research:

- What is the distribution of LULC diversity across two landscapes separated by an international boundary and with different socio-political histories, but otherwise similar?
- What magnitudes of LULC diversity are found in each landscape?
- What happens to the LULC diversity of each area over time?
- How do the patterns of diversity compare between the two landscapes?
- Can the patterns be interpreted – at least qualitatively – in terms of underlying mechanisms?

As stated in Chapter 2, we hypothesize that both landscapes will have left-skewed distributions at the micro-scale, approximately normal distributions at the meso-scale, and right-skewed distributions at the macro-scale (Figure 3-2). However, we expect that the specific distribution shapes for each landscape will differ in terms of the degree of skewness and kurtosis in the distribution, and that there will be variation in the precise shape of the distributions over time. At the micro-scale at any one location, individual agents will be able to select for only a few types of LULC from the large range of LULC types. Though individual types might vary

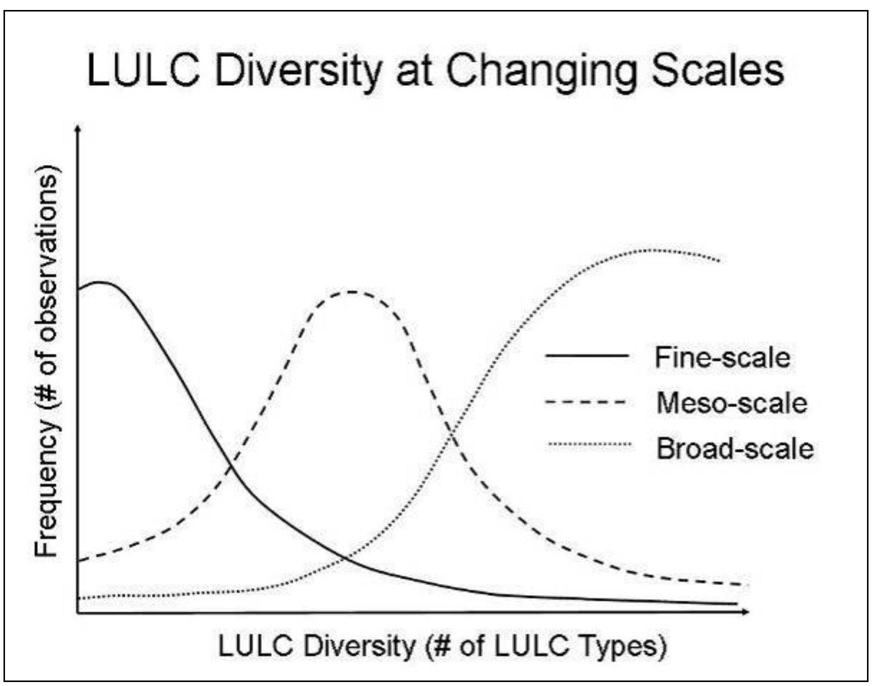


Figure 3-2. Schematic diagram representing the distribution of LULC diversity at different scales.

between locations, at the micro-scale low magnitudes of LULC diversity will be found. At the meso-scale, the collective selections resulting from the human-environment interactions occurring at the level below will produce a wide range of LULC types across the entire study area. This means that higher magnitudes of diversity will be present in some locations, but not others, as the presence of some types will be constrained in other locations by socio-economic and environmental factors. The broad macro-scale represents the context, and as such contains the full range of LULC types. At this scale, high magnitudes of LULC diversity will dominate.

Study Area

Large, regional, broad-scale comparative studies are useful for investigating the heterogeneity and dynamics of entire SESs (Turner, Gardner, and O'Neill 2001). This study examines two SESs as defined by the political boundaries of the cross-border provinces of Sisaket, Thailand and Ordar Mean Chey, Cambodia (but excluding the south-east corner of Sisaket which falls beyond the footprint of the satellite imagery). The study area was chosen because the two provinces have experienced very different political histories. The provinces currently exhibit highly dissimilar vegetation and socio-economic characteristics (Figure 3-3), in spite of similar underlying climatic biophysical characteristics. This provides an ideal opportunity to test whether LULC diversity as a concept can transcend context-specificity. The SESs are taken to be manifested by the LULC patterns distributed across the provinces – that is, the distribution of LULC types across the landscapes are a result of activities within the SESs (as detailed in Chapter 2).

Cross-border studies provide an opportunity to explore differences in the processes behind LULCC change (Bürgi, Hersperger, and Schneeberger 2004). Sisaket and Ordar Mean Chey, being spatially adjacent to each other, have the same edaphic, geomorphological and climatic contexts. Both are in the Asian monsoonal tropics, mostly flat, and have a few large rivers crossing them. They have pronounced, five- to seven-month, rainy seasons. Both were originally covered with semi-deciduous moist tropical forest. Geographically, the two provinces are separated by a low escarpment that drops from Thailand into Cambodia. Uplifting tilts the plateau back into Thailand so that the two provinces are separated hydrologically. Although the last couple of years have seen some cross-border trade, the provinces are for the most part socio-economically separate. They have been subject to different social, cultural, political and economic influences, partly because of the centuries-long antagonistic relationship between the two nations (Chandler 2000; Wyatt 1984).

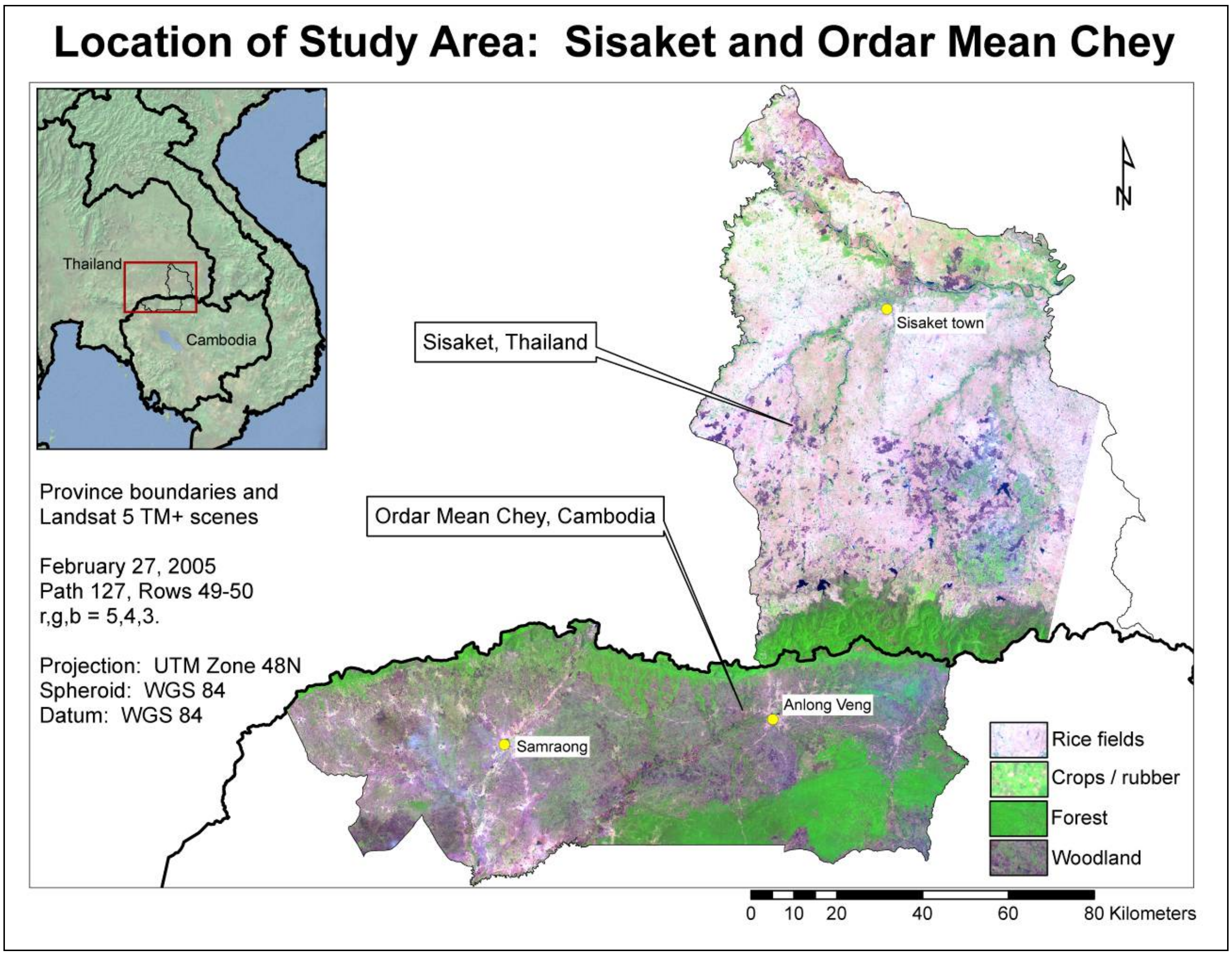


Figure 3-3. Study area map showing the different spectral characteristics of Sisaket, Thailand and Ordar Mean Chey, Cambodia

Sisaket is a predominantly agrarian province situated in north-east Thailand, at the southern edge of the Khorat Plateau. The north-east is drier and poorer than the rest of Thailand. Until recently, it lagged behind in economic and infrastructural development, as well as in agricultural expansion (Parnwell 1988). The province, measuring approximately 8860 km^2, is home to about 1.5 million people, with a population density of approximately 160 people/km^2. In spite of the region's relative poverty, nearly all rural villages are (as of 2005-2006) linked by paved roads and have electricity, clean water supplies, schools and health facilities. For the last several hundred years, the SES of this part of Thailand has centered on rice cultivation (Semthiti 1951; Wyatt 1984). Households are for the most part small-scale farmers, producing crops both for their own consumption and for sale. Sisaket's loss of forest cover mirrors that of the rest of the country (Sponsel 1998). Rice fields now dominate the landscape (Felkner 2000). Large tracts of forested areas are restricted to the extreme south, on the border with Cambodia, where the steep slopes of the escarpment mountains and border security policies and activities limit agricultural expansion.

Ordar Mean Chey shares the eastern third of its northern border with the western half of Sisaket's southern border (see Figure 3-3). It comprises an area of about 6630 km^2, with a population of about 70,000. Its population density, ~ 10 people/km^2, is an order of magnitude smaller than Sisaket's. It is one of Cambodia's poorest districts. The province was separated from Siem Reap province in the 1990s as the area it covered was still under the power of Pol Pot's Khmer Rouge, and as such, beyond the control of the national government. All roads are unpaved and seasonally impassable. Most settlements do not have electricity or formal water supplies. Forests and woodlands still dominate the landscape, although less so to the west of the province. The SES here can be defined as being one of subsistence farming and heavily reliant on natural resources extraction. Forest cover is rapidly being removed; both for timber harvesting and for slash and burn agriculture (Chan, Tep, and Sarthi 2001). Rice production is limited mainly to the western side of the province, closer to the district capital of Samraong. The eastern area is hilly, and less suited to rice production. Where fields are emerging in the east, these tend to be for upland crops.

Methods

Study Design

Both CASs and SESs are understood to be dynamic and changing, and yet functioning within defined spatial and temporal boundaries. The SESs of the provinces are represented spatially as gridded landscape models. Each grid cell, or pixel, contains a single value and represents a unit of sampling and analysis. Each pixel represents the LULC type present at that geographic location for a given point in time, and together all pixels provide a snapshot in time of each SES's "population" of LULC types. The term 'landscape' refers specifically to the spatial extent of each province and its constituent pixels. The study examines how diversity changes over a temporal extent of 16 years, from 1989 to 2005, and captured across 4 time-steps. This paper addresses the research questions separately for the two provinces, and then compares the results.

In order to study the influence of spatial scale on landscape patterning, LULC diversity is measured at three different spatial resolutions (Allen and Starr 1982). In terms of SESs, we note that decision-making is often made at the household level, contributing to the emergence of pattern at the community or village level. Broader political influences at the national and provincial level provide the context and constraints. Observations in the field, average district and commune sizes calculated from GIS data, and other studies suggest that the spatial extent of these different scalar influences would range from around 1 Ha (the order of magnitude of the average household land-holding), through the level of interest of a typical commune or district, with order of magnitude of 100 Ha, to about 100 km^2 – a scale that captures the cumulative effects of about 10 communes while still accommodating variation within the province (Chan, Tep, and Sarthi 2001; van Wey 2005; Mekong River Commission 2003; National Statistics Office 2003).

Determination of SES Components

The landscapes of the study area were "populated" with LULC types through the interpretation and classification of the six reflectance bands of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper + satellite imagery, with 30 m pixel resolution[3]. The study area falls across two scenes: WRS-2 Path 127 Rows 49-50. Cloud-free, seasonally comparable, paired scenes (sequentially acquired) were selected for four points in time across the study period: 22nd January 1989, 28th January 1994, 25th March 2000 and 27th February 2005 – all in the dry season of this north-east monsoon region. LULC types were identified during an initial visit to the study area in 2005, and after a second visit in 2006, a final set of 14 classes was determined to be a representative model of the two provinces' SESs. These classes were based on extensive field visits in 2005 and 2006, comparisons with related projects, and earlier maps (Blasco, Bellan, and Lacaze 1997; Mekong River Commission 2003; Nang Rong Projects 2004)

All images were radiometrically calibrated (Green, Schweik, and Hanson 2000; Markham and Barker 1986; Teillet and Fedosejeus 1995), and georectified using the 2000 image as the base. Each pair of scenes was mosiacked together and then subset to the study area. Classification of the 2005 image was done using a hybrid supervised-unsupervised iterative self-organizing data approach based on 276 randomly located training samples collected in 2006.

[3] The thermal band was omitted so that the classifications could be used in a separate study on within-class variation in temperature.

The accuracy of this classification was tested using 172 randomly located points collected in 2005, on a grouping of the classes into 7 categories, because the 14-class classification was fragmented into many 1-pixel patches. The spectral signatures generated by the classification of the 2005 image were then used to classify the earlier image subsets.

The resultant LULC classifications are considered the starting point for this study. The different measures of diversity at the three scales were calculated directly from these images. The 30 m pixel resolution, or grain, was considered appropriate for exploring patterns of LULC diversity, since the smallest possible window-size (3x3 pixels) corresponds roughly to the 1 Ha size of the lowest level of analysis. At this resolution and with this smallest window-size, nine (i.e. two-thirds of the maximum number) of the types can potentially be observed at the "contributing", household level of analysis, and at the community level of interest of 100 Ha, enough pixels are present to capture all 14 possible LULC types and to reveal detailed spatial patterns of diversity.

Calculation of Diversity for Fixed Points in Time

The two measures of diversity assessed in this paper are based on an analogy with species diversity in ecosystems. This does not mean that each LULC type is a 'species' in a SES. However, by using this theoretical parallel we can apply the analyses that have been developed for biological diversity to hypothesis tests for LULC diversity. We therefore assess both variety, a count of the total number of types in a given area, and relative abundance, the frequency of occurrence of each of the types. Since the classification process resulted in a total of 14 different LULC types, this value represents the maximum total variety possible in the study area, with 1 being the lowest possible value. In this study the Simpson's index of relative abundance is used, in the following form:

$$S = 1 - \Sigma (p^2/p) \quad (1)$$

where:

S = index value

p = proportion (McGarigal et al. 2002).

The Simpson's index runs from 0 to 1. In the form used here, 0 represents complete dominance by one type within the neighborhood of analysis, and 1 represents equal distribution of all types in the neighborhood.

Variety and relative abundance values for each pixel in the landscapes were determined by calculating the number and type of classes in a specified area surrounding the pixel through a moving window analysis. In order to capture the spatial extents appropriate to the three different levels of analysis, the size of the moving window was adjusted to include the different neighborhood sizes corresponding to each level: 3x3, 33x33 and 303x303 pixels (Table 3-1). For each time-step, three different variety, and three different relative abundance landscape models were generated based on the three different scales. The moving window analysis yields a series of maps that allows interpretation of the distribution of variety and relative abundance across the landscapes. The frequency distributions of the values across the pixels are further summarized through histograms and summary statistics, allowing comparisons between the two provinces and across time.

Table 3-1. Levels of analysis of LULC diversity

	Micro-scale Contributing level	Meso-scale Level of interest	Macro-scale Constraining level
SES level	Household / farm	Community	District / province
Spatial extent	~ 1 Ha	~ 100 Ha	~ 100 Km2
Analysis size	3x3 pixel window	33x33 pixel window	303x303 pixel window

Change in Diversity over Time

Because variety is an integer measure, trajectories of change in this measure of diversity can be calculated.[4] This was done for all three scales, by creating spatial outputs that represent the sequence of variety values in each pixel over the 4 time-steps. With 14 magnitudes of variety and four time-steps, there are an unwieldy 38416 potential trajectories; however, most trajectories will not be filled or to cover significant areas. This is because not all trajectories are plausible within the time-frame of the study. For example, it is unlikely for an extensive area of very high diversity to change to very low diversity, and then back to high, and then low, again.

Importantly, since the variety values are discrete and not categorical, for any given trajectory class the mean and variance of variety over time can be calculated, while still providing information on the directionality of change in the degree of diversity. Simpson's index analyses yields continuous data outputs, removing the option to calculate trajectories. For this reason, for each level of analysis, the standard deviation over time in Simpson's index was calculated for each pixel.

Results and Discussion

LULC Classifications

Although the classifications are the starting point of the diversity analysis, the results of the classifications are shown in Figure 3-4, and discussed here briefly. Several of the classes fall along a continuum of dense forest – less dense forest – dense canopy woodland – sparse canopy woodland – rice under sparse trees – treeless rice areas. Some of the classification errors reflect the effect of arbitrary cut-off points imposed along this range (Table 3-2). The most difficult class to separate from others was scrub / upland crops. This is a result of the classifications

[4] The term 'trajectory' refers to a category of change that groups together all areas that have the same specific LULC conditions at each of a series of time-steps. With continuous data, the variation is such that the likelihood of several pixels following the exact same sequence is minimal.

being based solely on the spectral characteristics of the satellite imagery, which in some instances are very similar for different LULC classes. The accuracy assessment for the grouped classes resulted in an overall accuracy of 85.5% and Kappa statistic of 0.779.

Table 3-2. Error matrix and producer's and user's accuracy for accuracy assessment of 2005 classification based on 172 reference points

	Reference Data						
Classified Data	Water	Forest	Woodland	Rice	Scrub / Crop	Rubber	Built
Water	4	0	0	0	0	0	0
Forest	0	49	4	1	3	0	0
Woodland	0	0	6	0	2	0	0
Rice	0	1	2	77	7	0	0
Scrub / crop	0	3	1	0	6	1	0
Rubber	0	0	0	0	0	4	0
Built	0	0	0	0	0	0	1
% Producer's Accuracy	100.0	92.5	46.2	98.7	33.3	80.0	100.0
% User's Accuracy	100.0	86.0	75.0	88.5	54.6	100.0	100.0

In Sisaket, the extent to which rice cultivation dominates the landscape is striking. Over the time period of the study, large areas of this SES have remained unchanged – not only the rice production areas, but also the forested border escarpment and riparian corridors. Some key changes have taken place, however. The extreme north-east, the escarpment foothills and the three hilly areas to the south-east have seen the emergence of upland crops, woodland and – most recently – rubber plantations.

On the other side of the border, Ordar Mean Chey's landscape reflects its troubled political conditions. From 1989 to 1994 there is a reduction in area under rice, and large increase in woodland, as the province experienced continued conflict, as landmines were laid down by both the new government and the retreating Vietnamese-backed factions. After 1994 the area began to stabilize, particularly in the west. This led to the reestablishment of rice fields, and increased settlement in the east. Associated with this settlement is a steady decline in forest cover. Most notable is the development of what was in 1994 a narrow track through the dense forest in the south-east of Ordar Mean Chey, into a dramatic wedge of deforestation by 2005.

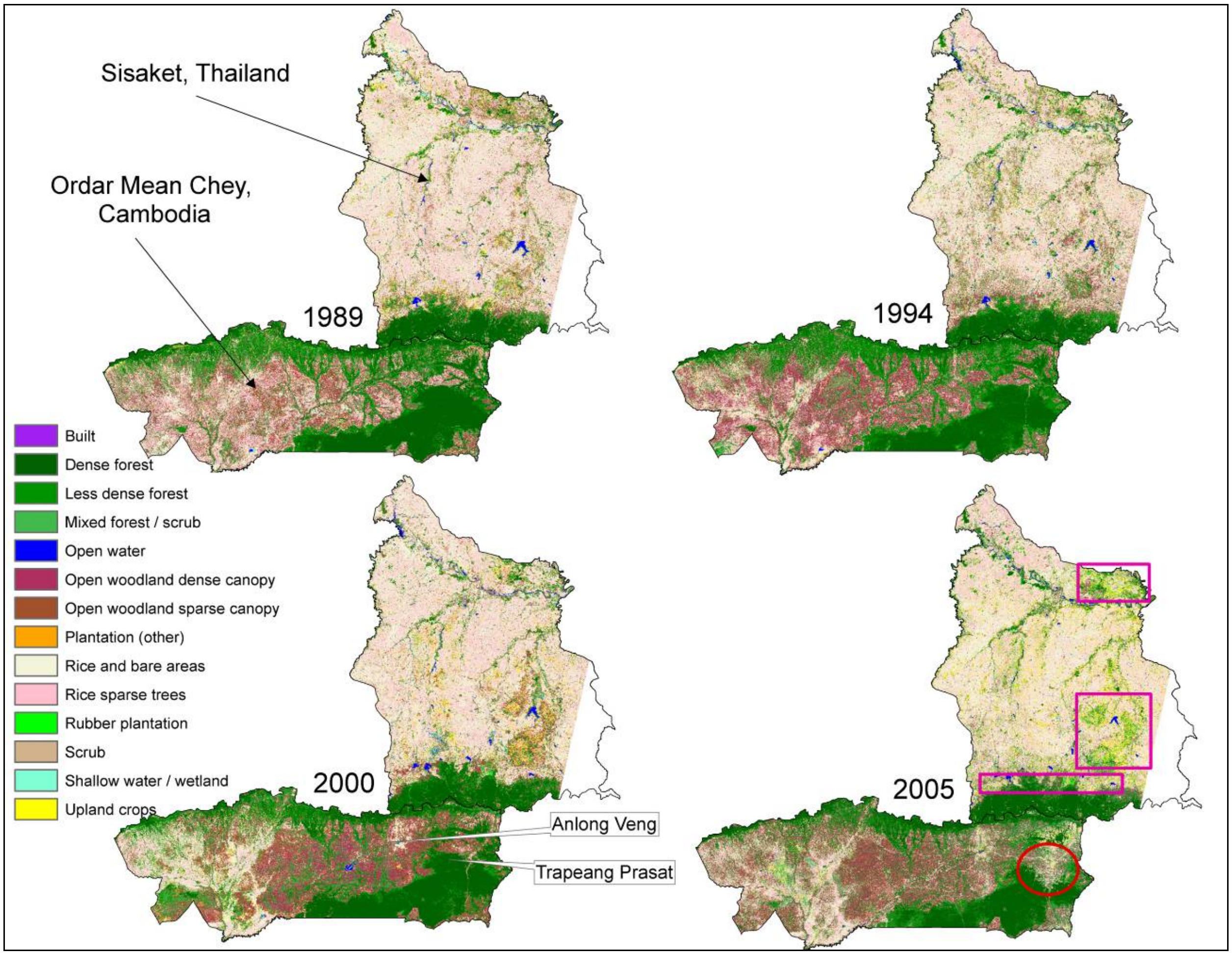


Figure 3-4. LULC classifications for Sisaket, Thailand and Ordar Mean Chey, Cambodia at each time-step in the study period. The circle on the 2005 classification shows the location of the wedge of deforestation in Ordar Mean Chey, while the rectangles highlight Sisaket's extreme north-east, escarpment foothills and three hilly areas, where woodland has given way to upland crops and rubber plantations.

Frequency Distributions of LULC Diversity

At the micro-scale the distributions are left-skewed, as hypothesized in Figure 3-2. The range of LULC variety is smaller, limited by the moving-window size. A high magnitude of variety would suggest a landscape so fragmented that at this scale, distribution of LULC types would appear almost random. In fact, as Figure 3-5 and Table 3-3 show, the mean magnitude of LULC variety is much lower, reflecting the ordered spatial structure that is visible in Figure 3-8.

Even though the mean values of LULC variety at the micro-scale are not substantially different for the two landscapes (Table 3-3), their frequency distributions have different shapes (Figure 3-5). While both are left-skewed, the distribution across the different magnitudes is more even for Ordar Mean Chey. The shape of the frequency distribution is roughly the same for each year in the Sisaket landscape, but in Ordar Mean Chey, the right-hand tail grows longer in 2005, as is reflected in the mean value for that year – which at 3.2 is noticeably higher than in previous years. This indicates that the Ordar Mean Chey landscape has experienced a considerable increase in the number of its LULC types for that time-step. The differences in the distribution patterns for each landscape suggest that there are fundamental differences in the driving mechanisms in each SES.

At this micro-scale, the distribution of relative abundance closely follows that of variety. For example, over the study period, both variety and relative abundance peak in 1994 in Sisaket, and in 2005 in Ordar Mean Chey. Note too the large increase in both the mean and median values for LULC relative abundance for Ordar Mean Chey for that year (Table 3-4). An examination of the original classifications and imagery shows that in 1994, there was a large increase in the amount of shallow water and wetlands across Sisaket which is attributed, on the basis of rainfall records, to the heavier rains associated with the previous year's El Niño event. Not only do these areas of water themselves add to diversity at the local level, but they also provide farmers an opportunity to grow an extra crop. While the Sisaket variation appears to be due to climatic fluctuations, the spatial arrangement of the patterns of diversity in Ordar Mean Chey suggests that in this SES, the increase in diversity is a response to settlement expansion.

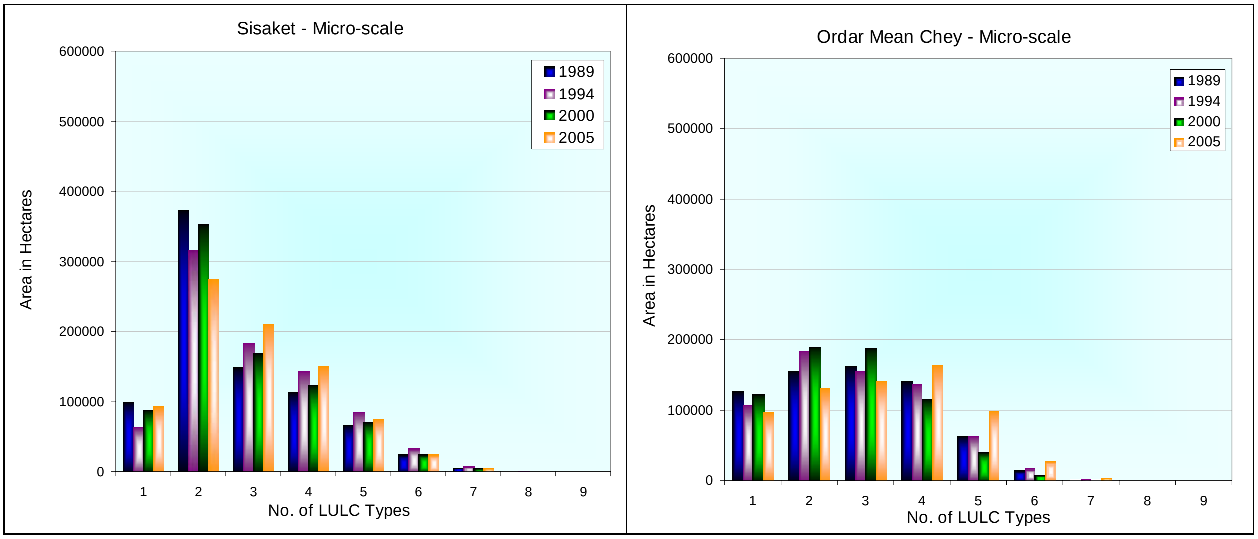


Figure 3-5. Frequency distributions of LULC types in 1989, 1994, 2000 and 2005 at the micro-scale

Table 3-3. Central tendencies of LULC variety at the micro-scale (3x3 pixel window)

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	2	2.72	1.30	3	2.85	1.34
1994	3	3.00	1.34	3	2.88	1.33
2000	2	2.79	1.28	3	2.68	1.21
2005	3	2.92	1.29	3	3.20	1.43

Table 3-4. Central tendencies of LULC relative abundance (Simpson's index) at the micro-scale

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	0.493	0.448	0.228	0.493	0.445	0.263
1994	0.493	0.494	0.215	0.493	0.450	0.253
2000	0.493	0.457	0.224	0.493	0.423	0.249
2005	0.493	0.471	0.231	0.590	0.498	0.256

As people have moved into the eastern parts of the province that was previously solely forest, they have cleared land using swidden techniques, creating patches of woodland, upland crops and rice. Repeated plowing has reduced the number of trees in some of the first-established fields. Houses and stores have been built. Each of these activities has increased the number of LULC types present.

The meso-scale is the scale at which patterns were anticipated to be most evident, because the 30 m grain-size allows enough pixels to be present in the 100 ha window to show where patterns emerge. Indeed, the frequency distributions and mean values of diversity for the two landscapes differ more from each other at this scale than they do at the micro-scale. At the meso-scale, the distributions are slightly more right-skewed than predicted, and the distribution of LULC variety in Ordar Mean Chey is bimodal in all years (Figure 3-6). This suggests that parts of the landscape, as detected at this scale, are more strongly influenced by social-ecological interactions, while others remain relatively untouched – such as the large areas of dense forest to the east where conflict between the Khmer Rouge and the national government restricted settlement. Due to political instability, the dense forests in the east have had almost no human population and have consequently experienced very little human activity. In the more stable

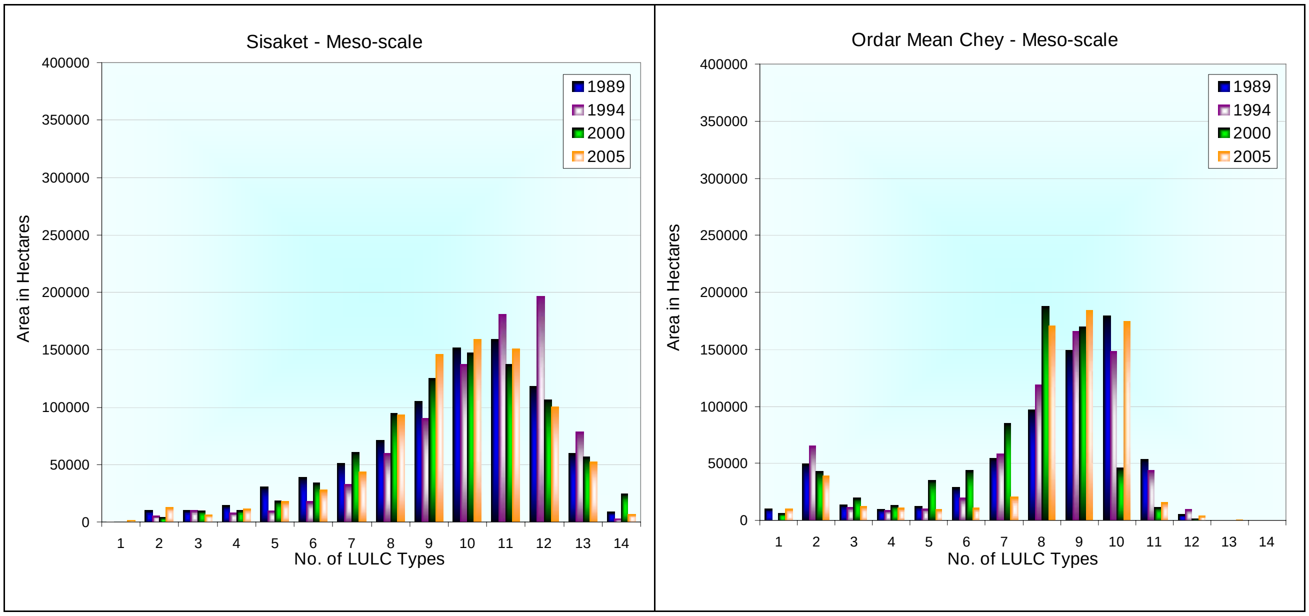


Figure 3-6. Frequency distributions of LULC types in 1989, 1994, 2000 and 2005 at the meso-scale

Table 3-5. Central tendencies of LULC variety at the meso-scale (33x33 pixel window)

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	10	9.58	2.49	9	8.10	2.60
1994	11	10.28	2.18	9	8.02	2.57
2000	10	9.68	2.34	8	7.36	2.25
2005	10	9.57	2.31	9	8.18	2.33

Table 3-6. Central tendencies of LULC relative abundance (Simpson's index) at the meso-scale

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	0.613	0.609	0.182	0.741	0.634	0.254
1994	0.671	0.650	0.164	0.726	0.633	0.230
2000	0.642	0.632	0.160	0.706	0.619	0.235
2005	0.673	0.646	0.173	0.777	0.677	0.228

west, people have implemented a range of land uses, including rice production, upland crops farming, grazing and hunting in woodlands, and harvesting forest products from different stages of forest succession.

Apart from this bimodality, Ordar Mean Chey as a whole also appears to exhibit considerable variation over time. At this scale, we are able to observe the strong decrease in both variety and relative abundance in Ordar Mean Chey in 2000 (Figure 3-6, Table 3-5 and Table 3-6), a trend that also exists at the micro-scale but which is somewhat overshadowed by the 2005 increases. Sisaket, on the other hand, appears to have a much more stable distribution across time – again with the exception of the 1994 increase in mean variety (Figure 3-6 and Table 3-5).

At the macro-scale, the distributions for both provinces are, as hypothesized, right-skewed (Figure 3-7). If the macro-scale is intended to represent the context, the differences in LULC variety between the two landscapes certainly support this. Firstly, the range of LULC types observed in Ordar Mean Chey was smaller than in Sisaket. Secondly, the median value of LULC variety in Sisaket has remained at the maximum for all four years, while in Ordar Mean Chey this value has dropped over time (Table 3-7). In addition, the Sisaket landscape shows much less variability at this scale, although this appears to be increasing slightly over time. The differences in spatial variability can also be seen graphically in the 2005 example given in Figure 3-8 (below). The patterns of the mean values for both variety and relative abundance at this macro-scale do not suggest any particular trend (Table 3-7 and Table 3-8). This makes sense if one considers this to be the scale of broader, slower-moving processes reflecting the provincial and national level.

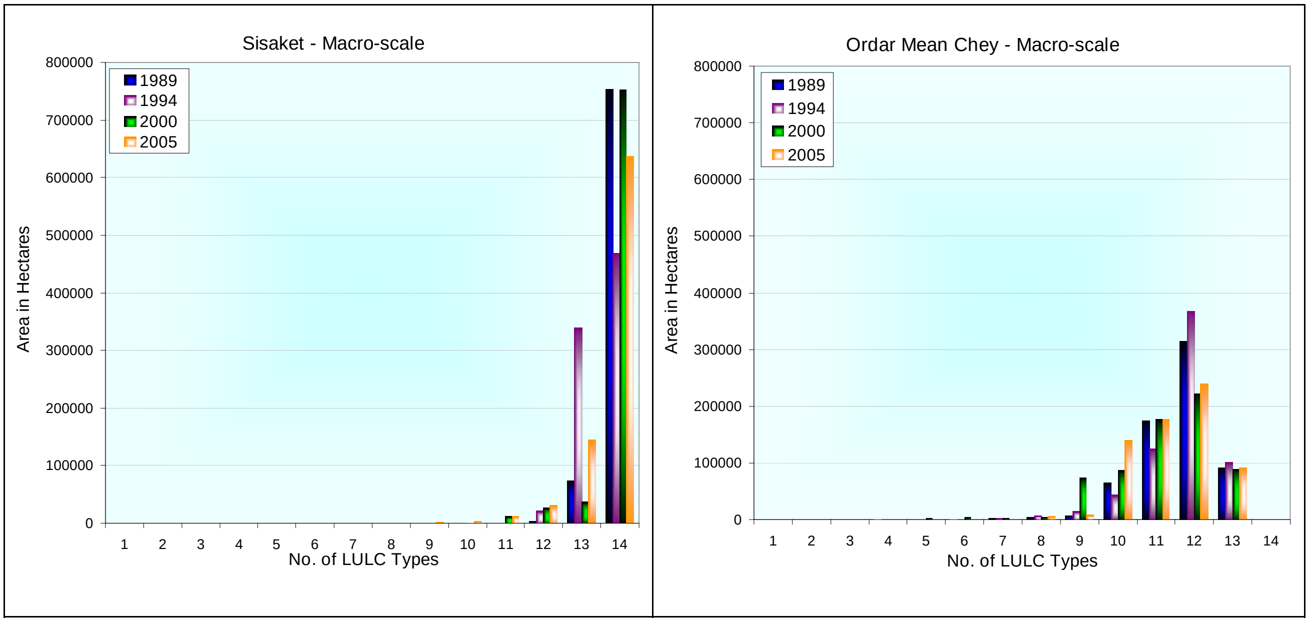


Figure 3-7. Frequency distributions of LULC types in 1989, 1994, 2000 and 2005 at the macro-scale

Table 3-7. Central tendencies of LULC variety at the macro-scale (303x303 pixel window)

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	14	13.91	0.31	12	11.58	1.05
1994	14	13.54	0.55	12	11.70	0.99
2000	14	13.84	0.56	11	11.15	1.37
2005	14	13.68	0.68	11	11.37	1.06

Table 3-8. Central tendencies of LULC relative abundance (Simpson's index) at the macro-scale

	Sisaket			Ordar Mean Chey		
	Median	Mean	Std Dev	Median	Mean	Std Dev
1989	0.658	0.659	0.130	0.791	0.708	0.214
1994	0.711	0.697	0.114	0.793	0.711	0.191
2000	0.684	0.685	0.109	0.780	0.706	0.197
2005	0.714	0.704	0.119	0.820	0.749	0.175

Not surprisingly, as we increase the scale, the mean values for LULC variety and relative abundance increase (Table 3-9 and Table 3-10). This is because the scaling up process used is similar to the ecological species-area curve, where the larger the area sampled, the greater the likelihood of capturing all LULC types. A comparison of the different mean values at the different scales, however, shows no consistent relationship between the scales over time, nor does there appear to be a strong link between variety and relative abundance. If the two measures were to follow the same trends in space and time, this would suggest that all LULC types were changing in the same manner with respect to their initial extent. However, socio-economic and environmental factors tend to select preferentially for some types more than others. For example, built areas emerge where settlements become established in the latter stages of the study period, and only account for very small proportions of changed areas. At the wedge of deforestation in Ordar Mean Chey, rice, crops and plantations do not replace forest in equal proportions. In Sisaket, some LULC types, such as rubber, that existed only in some localized parts of the landscape have emerged at more and more locations, whereas woodlands have been steadily declining.

Table 3-9. Comparison of mean LULC variety at three scales

	Sisaket			Ordar Mean Chey		
	Micro	Meso	Macro	Micro	Meso	Macro
1989	2.72	9.58	13.91	2.85	8.10	11.58
1994	3.00	10.28	13.54	2.88	8.02	11.70
2000	2.79	9.68	13.84	2.68	7.36	11.15
2005	2.92	9.57	13.68	3.20	8.18	11.37

Table 3-10. Comparison of mean LULC relative abundance at three scales

	Sisaket			Ordar Mean Chey		
	Micro	Meso	Macro	Micro	Meso	Macro
1989	0.448	0.609	0.659	0.445	0.634	0.708
1994	0.494	0.650	0.697	0.450	0.633	0.711
2000	0.457	0.632	0.685	0.423	0.619	0.706
2005	0.471	0.646	0.704	0.498	0.677	0.749

The frequency distributions and measures of central tendency show that LULC diversity is a useful, quantifiable SES characteristic. They show that there is a defined, non-random, structure to the distribution of both LULC variety and relative abundance. There are two main strengths to using LULC diversity as a landscape generalization. The first is that the distributions are shaped differently for the two provinces at all three scales, with the same general shape being held for each of the landscapes at different points of time. This general distribution is important, because it suggests that, at least in the short-term, the landscapes are maintaining their identity over time (Cumming and Collier 2005). These landscapes therefore provide information on the state of the two SESs, and show that LULC can indeed be used to represent SESs. The generalization to LULC diversity allows us to express spatial and temporal variation in the landscape as a whole, and to compare this overall variation in a quantitative manner, even where the *types* of LULC contributing to the variation might be different. For example, the SES in Sisaket is more diverse than that of Ordar Mean Chey. Since the two landscapes have the same climate and geophysical characteristics, the differences in overall magnitudes of diversity can be attributed to differences in socio-economic conditions. Even though Sisaket might have a greater range of activities within its SES, its landscape is dominated by only a few of those activities, whereas in Ordar Mean Chey, there is a much more equitable representation of the different activities on the landscape. If increasing dominance is an indication of path-dependency related to stage of adaptive cycle (Chapter 2), this would suggest that during the study-period, Sisaket was some way along the conservation (*k*) phase, while Ordar Mean Chey was still emerging from the exploitation (*r*) phase (see Gunderson and Holling 2002).

The second strength of LULC diversity as a landscape generalization is in the way in which – within each SES's general LULC diversity distribution shape – the measures of diversity vary over time. These variations contain important information. For example, across the study period, Sisaket had a peak of change in 1994, whereas for Ordar Mean Chey this was in 2005. This shows that each landscape, as a whole, is responding to different processes. Additionally, we can explore at which scale the variation is strongest. Since different underlying processes or mechanisms are scale-dependent, this information provides a guide to what those processes might be.

Spatial Distribution of LULC Diversity

LULC variety

A visual inspection of LULC variety shows that while patterns are discernable at all three scales of analysis, they are clearest at the meso-scale of interest (Figure 3-8). It is at this scale

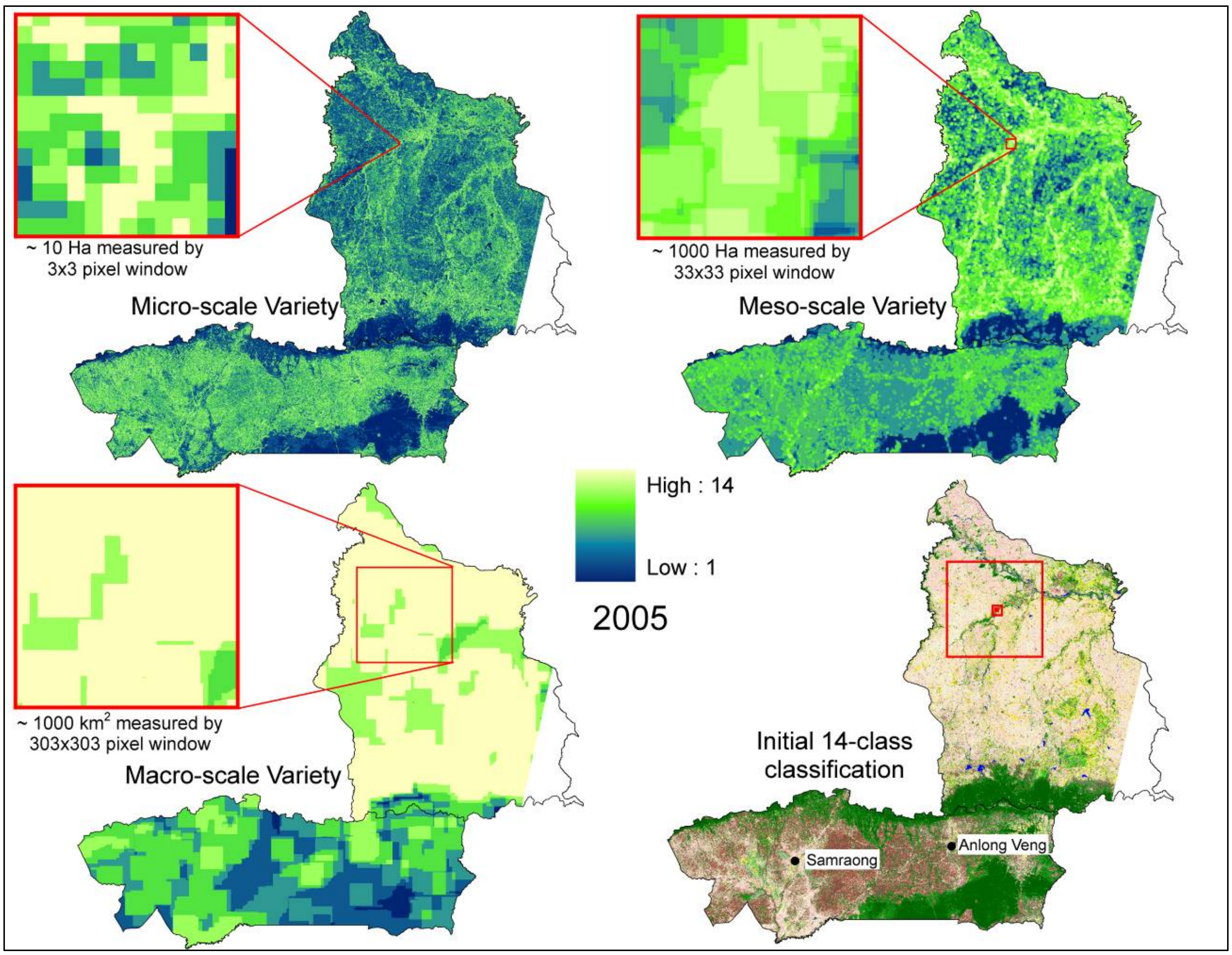


Figure 3-8. Spatial distribution of LULC variety in 2005, shown for the three different scales and in comparison to the initial classification. At the micro-scale, patterns appear more random, while those at the macro-scale appear more uniform. The insets, centered on the same riparian area, each cover a spatial extent representing roughly ten times the moving window size used for each scale, and are intended to show that these patterns are not solely due to the extent of the map, but also hold constant relative to the moving window size.

that one can clearly discern the effects of nodes and connectivity provided by settlements, roads and rivers. At this scale in Sisaket, which has been densely populated and intensely cultivated for centuries, high diversity follows the riparian corridors as well as the hilly areas already noted to the south-east and north-east of the province, and along the foothills of the escarpment. In Ordar Mean Chey, on the other hand, there are very few areas of high LULC variety. These areas are associated with the village of Anlong Veng, and with the road in the west that links the district capital of Samraong to the border in the north and the rest of the country to the south. At all scales, areas with less human-environment interactions generally have the lowest LULC diversity. Notable exceptions are the areas of extensive rice fields in Sisaket, which show how much this crop dominates the landscape at some locations. The macro-scale strongly reflects the national-level differences in the two SESs. At this scale patterns do not follow topographical features; instead they show the overall condition for each landscape.

LULC relative abundance

The maps of the Simpson's index show how equitably the different LULC types are represented at any given location. All three scales show that, in terms of relative abundance, Ordar Mean Chey's diversity appears to be spatially separated into areas of dominance by one type, and other areas where distribution of types is more even (Figure 3-9). This abrupt gradient of change suggests a frontier region, and is a consequence of the political conflict that has only recently abated to a level that allows development within the SES.

In Sisaket, there is much more of a smooth gradient between areas of dominance by one type, and those where most types are present. The north-eastern area, escarpment foothills and three hilly areas highlighted in Figure 3-4 also display much higher magnitudes of relative abundance. The well-established provincial capital of Sisaket town, which is located in the north-centre at the fork in the rivers, is clearly visible as a bright circle of high relative abundance of LULC types.

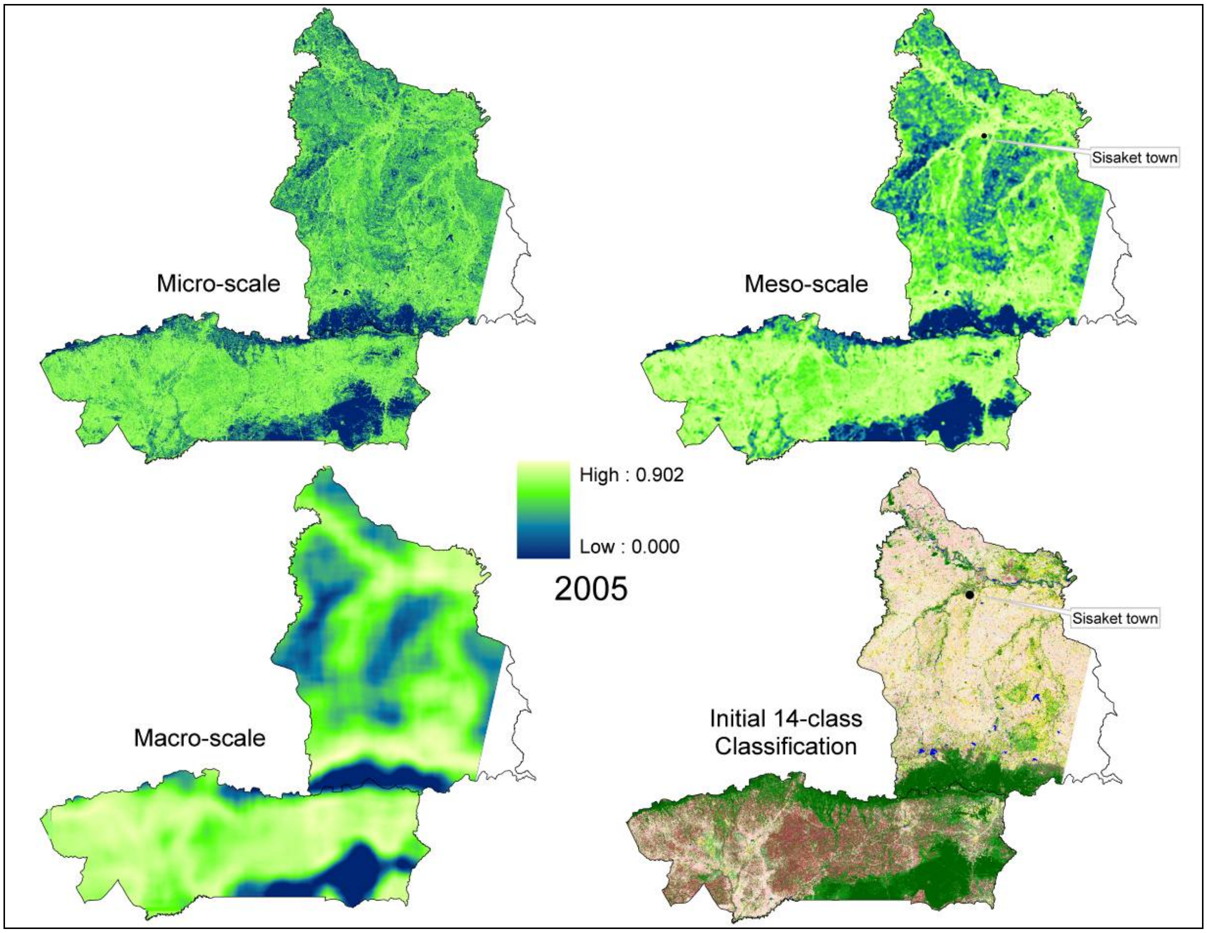


Figure 3-9. Spatial distribution of LULC relative abundance in 2005, shown for the three different scales and in comparison to the initial classification.

Even with a generalized landscape attribute such as LULC diversity, the information about the how the underlying mechanisms differ in each landscape is not lost. From even the most cursory examination of the diversity maps, it is clear that there is definite structure to the distribution of LULC diversity, both in terms of variety and relative abundance. One can trace the patterns of diversity relative to social and environmental features, such as roads, market villages, rivers and hilly areas. At each scale we can see differences between the two SESs in terms of the spatial distribution of their LULC diversity. At the micro-scale, Sisaket has a more spatially ordered structure to the distribution of the number of LULC types. At the micro-scale, the Sisaket SES is so highly connected by its network of roads and settlements, that these appear to have less of an influence on LULC variety than environmental factors do. Much of its landscape has areas of intermediate LULC diversity, with high diversity located along river systems and in gently sloped hills. Areas of low LULC variety are restricted to steeper, forested escarpment of the protected border area. At this scale, in contrast, Ordar Mean Chey's landscape appears to be a complex mix of high and intermediate LULC variety, with the hilly forests in the south-east being the most discernible exception. At the meso-scale, the patterns in Sisaket do not change relative to the micro-scale, but become more marked. In Ordar Mean Chey, however, we begin to see roads and villages stand out as nodes and linear features of higher diversity. In this SES, accessibility is still key in determining LULC variety distribution.

Perhaps unsurprisingly, it is at the macro-scale of LULC variety that the contrast between the two provinces becomes most evident, although the degree to which the two SESs differ is remarkable. This difference underscores the extent to which their different national identities have subjected the provincial-level SESs to different contexts and different sets of constraints (Allen and Starr 1982). Access and economy, as part of these contextual factors, determine the level of infrastructural development. The spatial arrangement of LULC variety suggests that infrastructure is well-developed all over Sisaket, while in Ordar Mean Chey, it is limited to localized areas surrounding the few major towns.

LULC relative abundance is a more nuanced measure of diversity than LULC variety, and this is evident in the maps, particularly at the macro-scale. Nevertheless, the Simpson's index maps also show strong differences between the two provinces. While Sisaket shows a good range in degree of dominance by some LULC types, in Ordar Mean Chey, there appears to be either complete dominance by one type (dense forest), or a relatively equitable distribution of all present types. In Ordar Mean Chey these patterns relate to rapid recolonization of an area that was inaccessible for a long period. In Sisaket, on the other hand, access is less of a limiting factor because there are so many roads. The relative abundance patterns also suggest that LULC diversity is linked to environmental conditions, such as areas of higher soil fertility that are found along the rivers or in the escarpment foothills.

Change in Spatial Distribution of Diversity over Time

Apart from minor fluctuations, the Sisaket landscape shows no substantial change in overall magnitude of diversity over time, suggesting that at least for the period of study this landscape as a whole is stable (Figure 3-10). Temporal variation seems to be limited to a slight

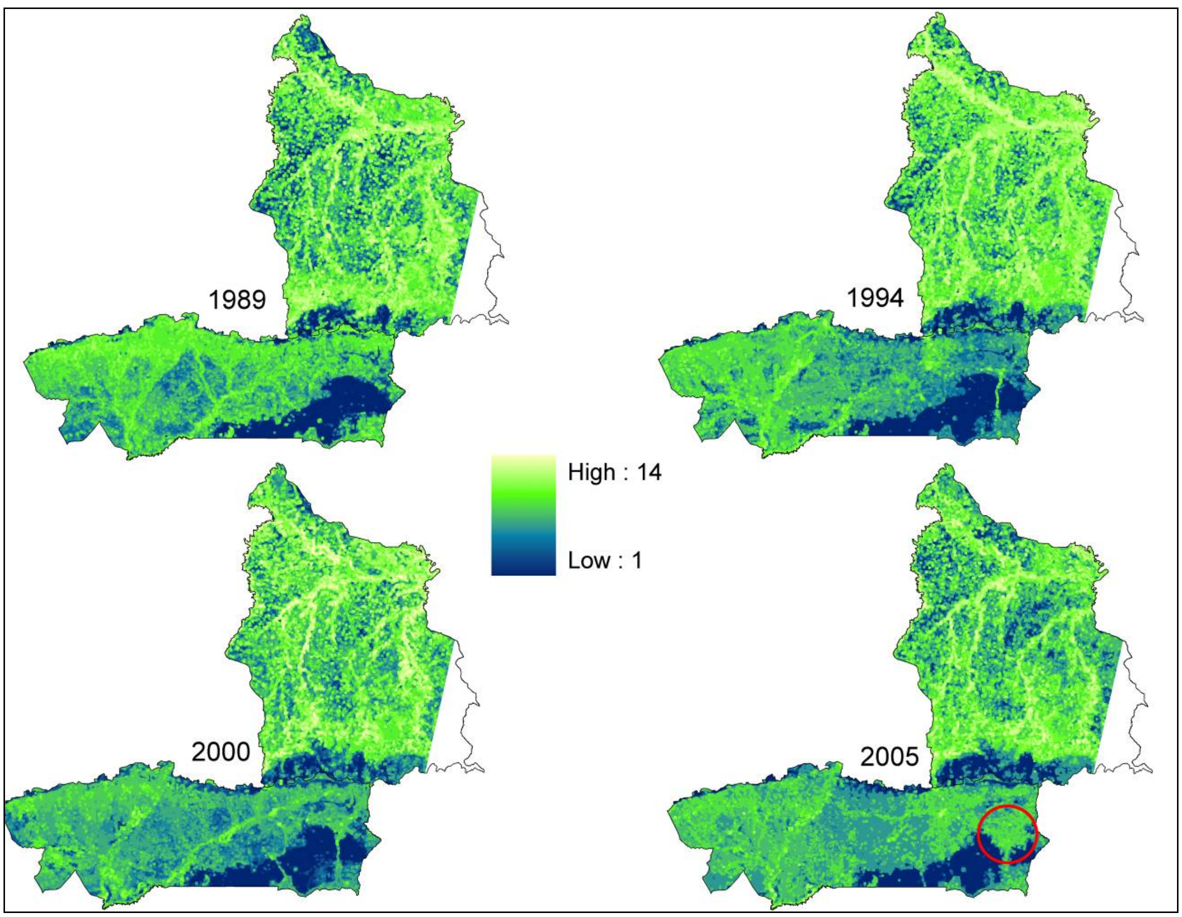


Figure 3-10. Spatial distribution of LULC variety in 1989, 1994, 2000 and 2005, shown at the meso-scale. The circle on the 2005 map shows the wedge of deforestation.

increase in diversity in 1994 before returning to a more intermediate overall magnitude in 2000 and 2005. This fluctuation is possibly due to the effect of increased rains from the previous year's El Niño conditions. In 1994 there was an increase in the area of shallow water and wetlands, and in the areas of upland crops and other plantations. In Ordar Mean Chey, the changes are more dramatic. Most notable is that the wedge of deforestation visible in the south-east in Figure 3-4 is now visible as a wedge of increasing LULC diversity. The effect of access on LULC diversity is also visible as ribbons of high diversity cut through areas of lower diversity as a consequence of the development of roads and settlements.

Temporal Trends in LULC Variety and Variation in LULC Relative Abundance

The trajectories of change in LULC variety across the four time-steps were created for all three scales. These were done across the entire study area, treating the two provinces as a single surface to highlight the extent to which certain trends were taking place only in one of the two landscapes. As anticipated, not all of the potential trajectories were filled, and only a small fraction – 19 trajectories (0.28% of those possible) at the micro-scale, 370 (0.96%) at the meso-scale, and 143 (0.37%) at the macro-scale – covered areas of 10,000 pixels (9 km^2) or more, hereinafter called 'extensive trajectories'.

By plotting out mean LULC variety over time against the variance in LULC variety over time for each trajectory, we can see what types of trajectories are missing. Figure 3-11 shows the potential, actual and extensive trajectories, with each point representing a specific trajectory. The first row shows the plots for every possible combination of LULC variety across the four time-steps, whether that combination was found in the study area or not. Most of the points are concentrated in areas of the graphs that relate to intermediate magnitudes of diversity, and low variance. A comparison of the actual-occurring trajectories with all potential ones shows what combinations of LULC variety magnitudes are likely in the real world, and what types of trajectories account for the dominant patterns on the landscape. The graphs in Figure 3-11 show that large swings from high to low to high to low diversity at any location are conceptually unlikely – most of the missing trajectories, at all three scales, are those that have both high means and variances. Indeed, when considering only those trajectories that cover extensive areas, there are none which have the highest theoretically possible variance. The circles on the

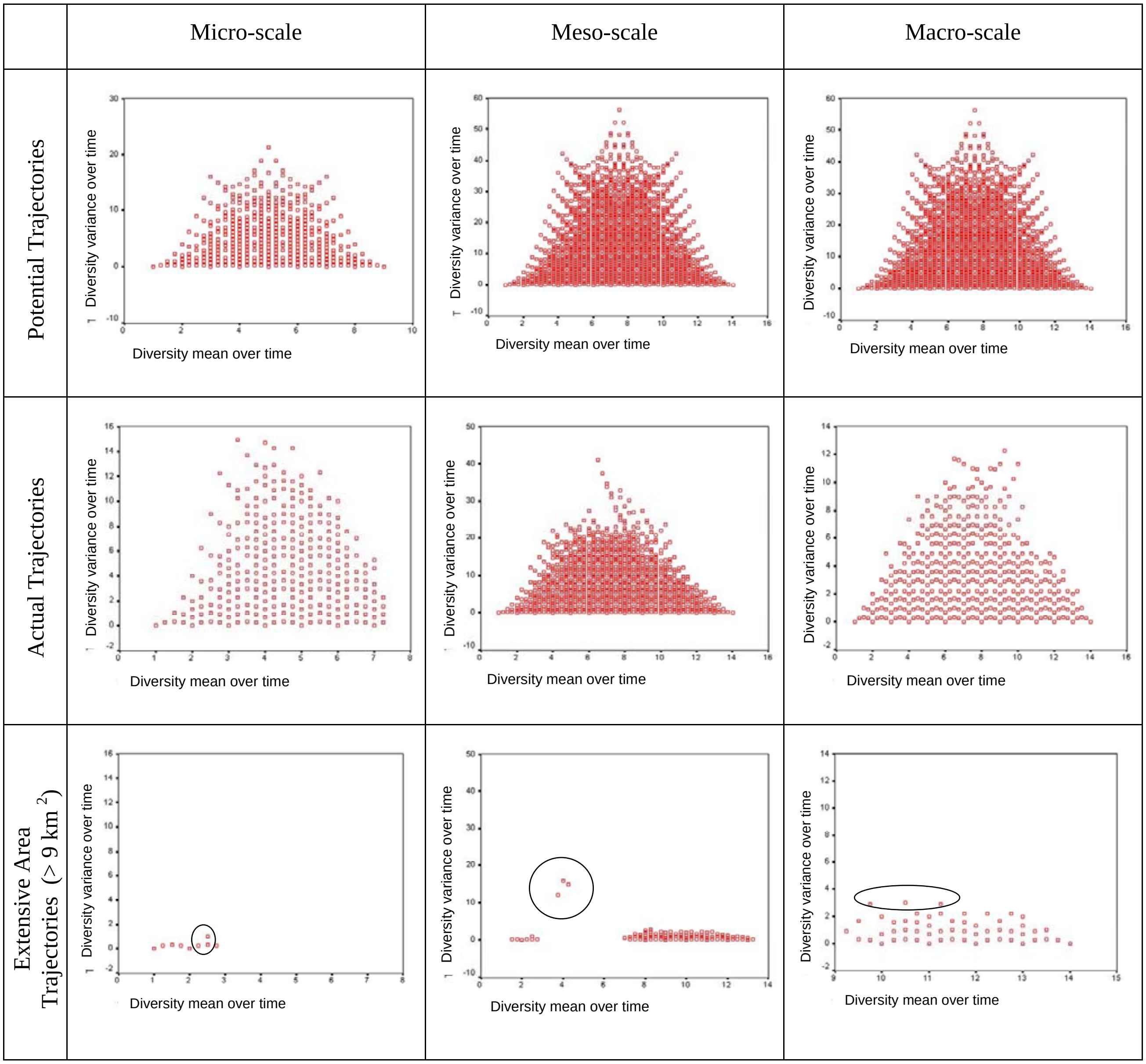


Figure 3-11. Scatterplots of mean LULC variety vs. variance of LULC variety for the combined study area, comparing values for actual and extensive trajectories against all theoretical potential trajectories. Extensive areas with the greatest variance are circled.

graphs representing extensive areas identify those trajectories that both cover large areas, and have the highest observed variance. These trajectories are the ones that represent the greatest change in magnitude of diversity. By focusing on these extensive trajectories with the highest variance over time, we can identify the most dynamic parts of the landscape.

At the micro-scale, the trajectories of diversity that cover the greatest extent are all areas that remained at low magnitudes of diversity across the entire time period (Figure 3-12). The most extensive trajectory is, in fact, that with only one type of LULC, corresponding to undeveloped
forested areas, occurring in the hilly regions of both provinces' landscapes. The second most extensive trajectory is that where there are only 2 types of LULC types at all four time-steps. Note, however, that in Sisaket, this relates to areas of rice production, while in Ordar Mean Chey, it relates to riparian forest. The third most extensive trajectory at the micro- scale shows a slight increase at the end of the trajectory period, and occurs far more extensively in the Sisaket landscape than that of Ordar Mean Chey.

The fact that the most extensive trajectories at this scale have such little variance, and such low variety at all points of time, might seem to be imply that at the micro-scale, the entire landscapes is homogeneous and unchanging. However, these three trajectories together account for only 14.9% of Sisaket and 9.3% of Ordar Mean Chey.   Since the rest of the landscape is covered by other much smaller trajectories, in fact both provinces are both spatially and temporally variable at this scale.

As with the "static" analyses shown in Figure 3-5 to Figure 3-7, the dominant trajectories reflect the influence of scale, increasing in mean value (Figure 3-11) as the scale shifts upwards. At the meso-scale, the spatial distribution of each of these trajectories is once again location specific, in spite of appearing somewhat patchy (Figure 3-12). As with the micro-scale, all of the most extensive trajectories have very little variance. At this scale, the most extensive trajectories occur mainly in Ordar Mean Chey. The bimodality for this province's landscape that is evident in Figure 3-6 is picked up again in the trajectories and reflects path-dependency – that is, areas that were initially extensive in 1989 will determine which extensive trajectories are possible. While the most extensive trajectory is at an intermediate magnitude of LULC variety, the second-most extensive is at a low magnitude. This second-largest trajectory is associated with the forested areas to the south-east, while the other most extensive trajectories are all located in the western part of the province where internal conflict remained relatively lower. The fact that

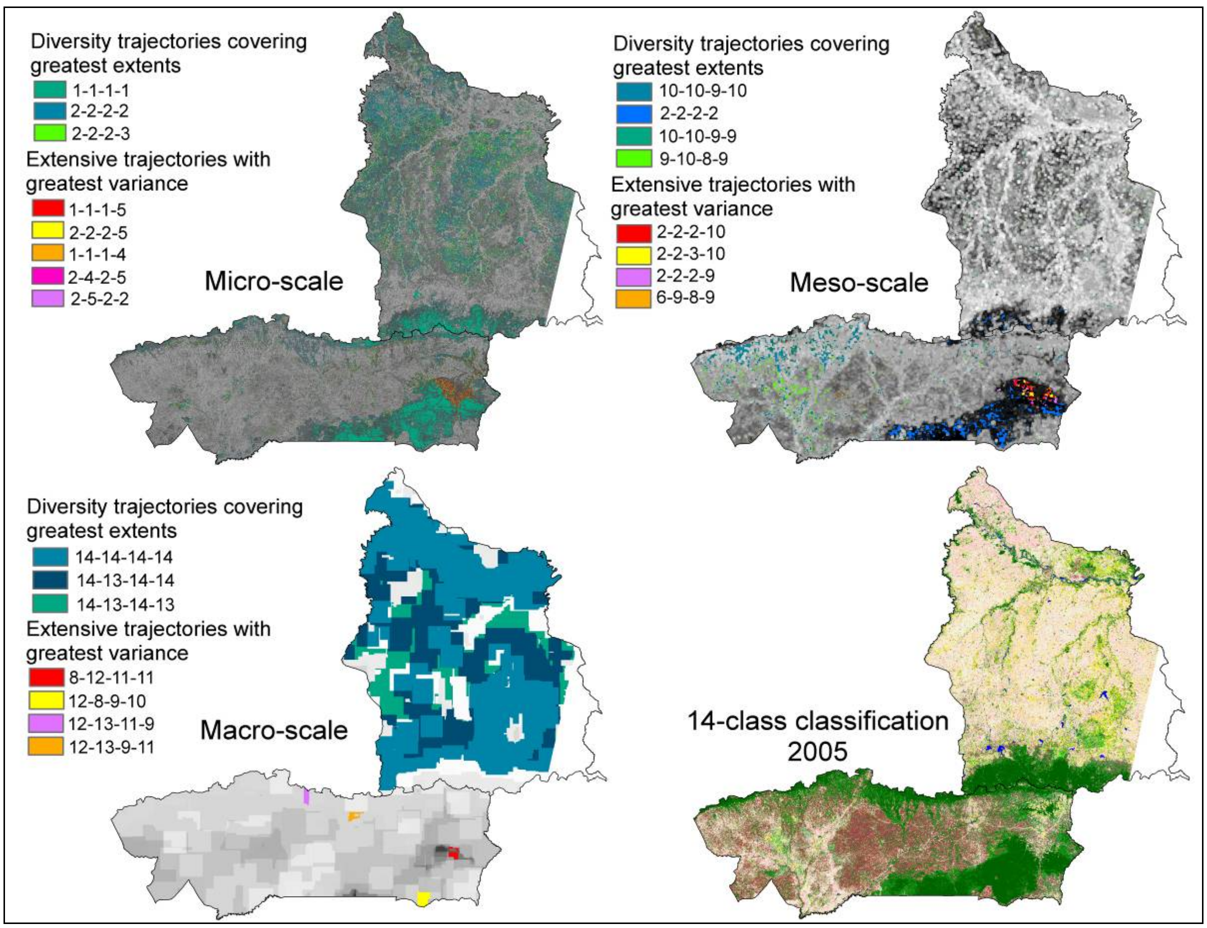


Figure 3-12. Spatial distribution of trajectories of change in diversity derived for each scale from that scale's four time-steps of LULC variety. Each number in the legend name represents the number of LULC types in the relevant pixel-window neighborhood at each time-step.

such small areas (less than 0.9 % of Sisaket's landscape) of the extensive trajectories are found in Sisaket suggests that in this province there is great variability in magnitudes of diversity at the community level. The influence of the national-level context is clearly evident at the macro-scale. The extensive trajectories dominate the Sisaket landscape (80.6%), but are entirely absent from Ordar Mean Chey (Figure 3-12). The trajectories are all of persistently high magnitudes of LULC variety, in strong contrast to the micro-scale.

Turning to the extensive trajectories with the greatest variance in LULC variety over time, the most striking fact is that, at all three scales, the greatest variance occurs in the wedge of deforestation in the far west of Ordar Mean Chey – and almost exclusively at that wedge (Figure 3-12). Dramatic change is not occurring anywhere in Sisaket, and only at the macro-scale do places in Ordar Mean Chey other than the deforestation wedge show considerable variation. Note that for each high-variance trajectory at this broad scale, a single contiguous area is affected. The northern-most block of change (12-13-11-9) relates to the opening of a border-post with the Thai province adjacent to Sisaket. South and east of that is the town of Anlong Veng (12-13-9-11). The similarity of these two trajectories is a reflection of the opening up of this part of the province with the declining influence of the anti-government Khmer Rouge party, leading to increased settlement, clearing of land, and diversification of land-uses in response to economic demands.

From the sequence of the values of diversity in the trajectories, we can also see the directionality behind that variance. At all three scales most of the area under the high-variance trajectories shows a trend of increasing LULC variety over time. At the micro- and meso-scales, it is clear that most of the change in Ordar Mean Chey occurred between 2000 and 2005. Although the values for the most variable macro-scale trajectory, and the timing of the increase in magnitude of LULC variety, differ from those in the other scales, the location – at the core of the deforestation wedge – is exactly the same.

Due to the continuous nature of the Simpson's index, it is not possible to produce meaningful trajectories of change in LULC relative abundance. Nevertheless, the standard deviations over time are still revealing – in spite of the non-directional nature of these data. The maps of standard deviation in LULC relative abundance over time (Figure 3-13) show that this measure, like that of LULC variety (Figure 3-12), is most variable at the wedge of deforestation in Ordar Mean Chey. Again, this dramatic change is visible at all three scales.

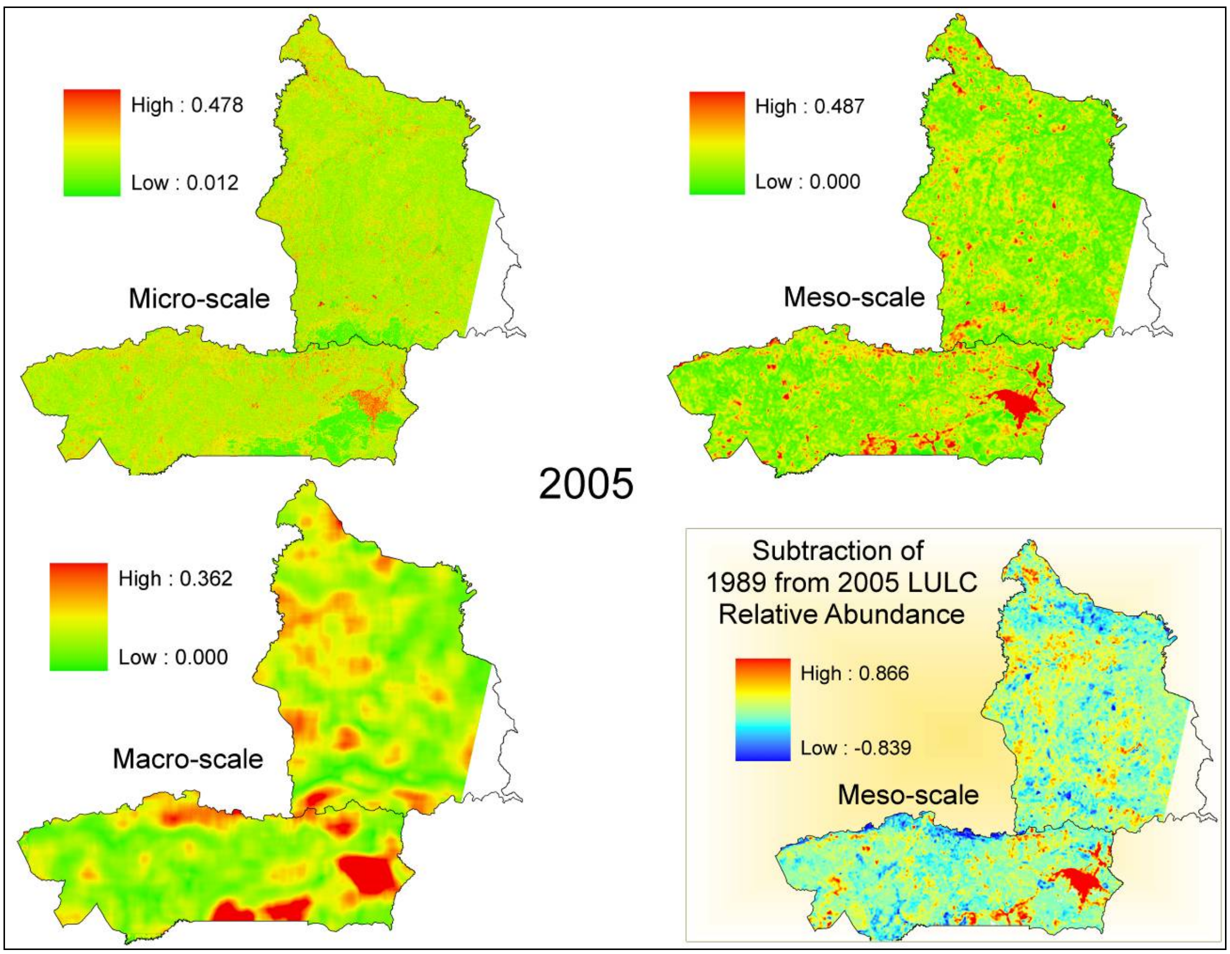


Figure 3-13. Spatial distribution of temporal variation in LULC relative abundance, calculated for each scale as the standard deviation of the values for each time-step at that pixel. The inset map shows that not all change is an increase over time, as some places (with negative values) experienced a net decrease in relative abundance between 1989 and 2005.

At the micro-scale, which shows the effects of household-level decision-making, the landscapes in both provinces show that some areas have a fair amount of variation in relative abundance. Sisaket has a mean value of 0.147 in standard deviation for its whole landscape at this scale, while in Ordar Mean Chey this value is 0.152. This suggests that in both provinces farmers engage in different activities at the same location from year to year. At the meso-scale, which relates to the community, considerably less variation is expressed in both landscapes (Sisaket 0.062, Ordar Mean Chey 0.073), even though in the latter province there is extensive change.

When we consider the mean magnitudes of diversity for each SES, the overall variation over time is minimal. This makes sense because the study period represents only a short segment of each SES's history. Indeed, the short duration adds significance where some places have experienced significant change. If we look at both diversity measures and all scales at the same time, there do not appear to be any definite trends in the mean magnitudes of diversity for the landscapes as whole SESs over the 16-year period. Instead, there appear to be fluctuations within essentially stable (in this short-term) magnitudes of LULC diversity. Within each of the whole landscapes, however, considerable change is taking place in specific, more localized areas.

If we express these landscape changes in the language of CASs, we can see the graphs of the means and variances of the LULC variety trajectories as evidence of non-random structure leading to the emergence of patterns of change. Not only have some of the unlikely potential trajectories been winnowed away, but only a few trajectories cover extensive parts of the landscape (see Chapter 2). This means it is easy to identify dominant trends within each SES, not only in terms of what those trends are, but also where they are located. The most extensive trajectories suggest that there is some directionality and path-dependency, where initial conditions appear to be dictating what follows afterwards, and whether a given magnitude of LULC variety will persist over time.

It is the high variance trajectories that most support the idea that LULC diversity is a useful generalization that allows cross-site comparison while still capturing important change in a landscape. The fact that Ordar Mean Chey's area of deforestation is prominent in each scale of both measures of change in diversity shows clearly that diversity has meaning on the SES landscape. If the assumption of LULC as an expression of a SES is correct, the location of the most extensive trajectories in the more politically stable west of Ordar Mean Chey suggest that complexity in this area of the SES is being developed.

Further Studies

Having established that diversity as a SES characteristic is detectable in LULC landscapes, and that landscapes can be compared and contrasted in terms of this concept, the next step is to test how LULC diversity responds to known drivers of LULCC, since typically it is through an understanding of the causes of change that researchers are able to predict and plan for that change. In this paper we have qualitatively described some of the factors that might underlie existing diversity patterns, or lead to changes in the distribution of diversity. If a formal analysis of the response of diversity to these factors is as revealing as exploring how actual LULC types respond, then this would provide a path out of the context-specificity that is currently beleaguering researchers. From the patterns observed on the landscape, we hypothesize that LULC diversity is generally higher closer to roads and market settlements, factors that influence accessibility, and that are known to lead to change in specific LULC types in other places (Southworth and Tucker 2001; Verburg et al. 2002; Walker and Soleki 2004). In addition, in both Sisaket and Ordar Mean Chey, low LULC diversity appears to be located in higher areas with steeper slopes, factors that have been associated with the distribution of specific LULC types (Mas et al. 2004; Overmars and Verburg 2005). In Sisaket, areas of high diversity are located in the kind of low-lying hills that are associated with more fertile soils – which are associated with high rates of LULCC in the lowlands of Colombia (Etter et al. 2006). The combination of stability over time of diversity magnitudes with high population density in Sisaket suggests that land tenure plays an important role in regulating magnitudes of LULC diversity, much as land rights affect agricultural expansion and other forms of LULCC (McConnell, Sweeney, and Mulley 2004). These, and other, hypothesized relationships can form the basis for comparing the response patterns of different diversity landscapes to underlying mechanisms.

Other methods of accommodating the scale effect could be usefully explored, such as trying different grain sizes. Slight adjustments might increase the emergence of patterns, while larger grain sizes could reduce processing time while still revealing the same information. It would also be useful to experiment with merged or grouped LULC categories, as this represents another way of scaling up. In theory, a grouped classification of around 6 classes, such is more commonly used by land change scientists, should yield results with similar means but greater variances.

Finally, additional consideration could be given to increasing the time period. Palaeo-ecological studies of historical societies show that successful SESs persist for hundreds of years (Binford et al. 1997; Janssen, Anderies, and Ostrom 2007). To adequately pick up trends over this temporal extent, studies should span at least three generations of the dominant organism – humans. This would suggest a period of approximately 75 to 100 years. At present this would require turning to alternative sources than remote sensing to provide maps of the earlier LULC states – particularly in developing countries. However, new techniques are being tried, and as time passes, the aerial photograph and satellite imagery datasets are providing longer windows of analysis.

Conclusion

This paper represents a necessary first step in evaluating the utility of LULC diversity in linking LULCC to SESs research: the verification that it is indeed possible to use the concept as a generalization for comparing and contrasting different SESs. That human activities generally lead to greater LULC diversity is perhaps obvious. What is less obvious is that these landscape patterns can be used by SESs researchers to evaluate the condition of a SES of interest. Framing LULCC in concepts used in that field makes the spatial, quantifiable information founded on LULCC available to them. This research shows that LULC diversity is distributed in distinct patterns across the landscapes of the two study area SESs. These spatial patterns show that different underlying processes linked to the roles of rivers, soil, elevation, roads and settlement are visible at different scales. LULC diversity provides a way to quantify SESs as expressed on the landscape, and as such can be used to measure system characteristics such as change and persistence (Carpenter et al. 2001; Cumming et al. 2005). Because the LULCC approach is spatial, a focus on changes (or not) in LULC diversity reveal where system identity is changing or persisting.

By treating landscapes as SESs, LULCC researchers can draw on generalizations from CASs theory – such as diversity – to compare change in different landscapes in their entirety – even where the nature of that change might differ because the landscapes comprise different LULC types. The research described here leads us to conclude that LULC diversity serves as a unifying, non-ecosystem specific characteristic for cross-site comparison. As such it offers researchers the potential to overcome context-specificity (Perz 2007). As a quantifiable concept, LULC diversity offers an additional advantage over the standard classification approach to

LULCC. Because the measures of diversity are discrete (variety) and continuous (relative abundance) as opposed to categorical, this increases the options for exploring spatial and temporal variability in a quantitative manner.

As a theoretical construct, LULC diversity provides additional insight into the human-environment interactions that are shaping our world, particularly when considered through the framework of a CAS. Diversity can be evaluated at different scales, reflecting the multi-scalar nature of SES processes (Ahl and Allen 1996). The spatial arrangement of LULC diversity suggests that the SESs are self-organizing, with patterns emerging from interactions at lower levels (Holland 1995; Levin 2005). Magnitudes of diversity at any given location within the landscape can decrease as some LULC types are winnowed away, or increase, as new types evolve – such as the conversion of rice fields to upland crops and rubber plantations (Levin 1999). Change in LULC diversity is non-linear, as evidenced by the change trajectories with high variance. This threshold-type response is another characteristic of a complex, adaptive SES (Folke et al. 2004; Holland 1995; Holling and Gunderson 2002).

By linking LULCC to SES research through the CAS framework, we are able to provide the former with the necessary concepts to develop an umbrella deductive approach for guiding the emerging discipline of land change science (Rindfuss et al. 2004). At the same time, by using LULC as the physical expression or representation of a SES, we provide the latter with the means to start quantifying certain types of SESs (Carpenter et al. 2001; Cumming et al. 2005).

CHAPTER 4
SOCIAL AND ECOLOGICAL FACTORS AND LAND-USE LAND-COVER DIVERSITY IN TWO PROVINCES IN SOUTH-EAST ASIA

Introduction

Studying human-environment interactions through the lenses of land-use land-cover change (LULCC) and social-ecological systems (SESs) research offers a broader perspective, but each approach faces certain challenges. LULCC research has excellent tools to measure landscape-level change, but is struggling to develop a theoretical framework that is generalized enough to surmount disciplinary boundaries or the complexities of comparisons beyond specific locations (Bürgi, Hersperger, and Schneeberger 2004; Carpenter et al. 2001; Kuhn 1996; Perz 2007; Walker 2004). On the other hand, SESs research – that is, research conducted through programs such as the Resilience Alliance that specifically focus on incorporating both social and ecological aspects through a systems approach – was developed under the umbrella of a broad conceptual framework – that of complex adaptive systems (CASs) – but, with a few exceptions, has been unable to find ways to quantify change (Chapter 2; Cumming et al. 2005; Carpenter et al. 2001, Anderies et al. 2006). Since these research programs both address the dynamics of human-environment interactions, it seems apposite to explore whether the strengths of each can address the weaknesses of the other (see Figure 4-1).

This study explores empirically how LULC diversity, as a higher level CAS characteristic, responds to the biophysical and socio-economic factors that are known to influence change at a lower level - in individual LULC types (Alados et al. 2004; Bürgi, Hersperger, and Schneeberger 2004; Chomitz and Gray 1996; Crews-Meyer 2004; Douglas 2006; Erenstein, Oswald, and Mahaman 2006; Etter et al. 2006; Munroe, Southworth, and Tucker 2002; Overmars and Verburg 2005; Van Gils and Loza Armand Ugon 2006). It explores the distribution of LULC diversity in response to elevation, distance to roads, and distance to markets, and evaluates how the resultant distributions compare to hypothesized relationships (Chapter 2).

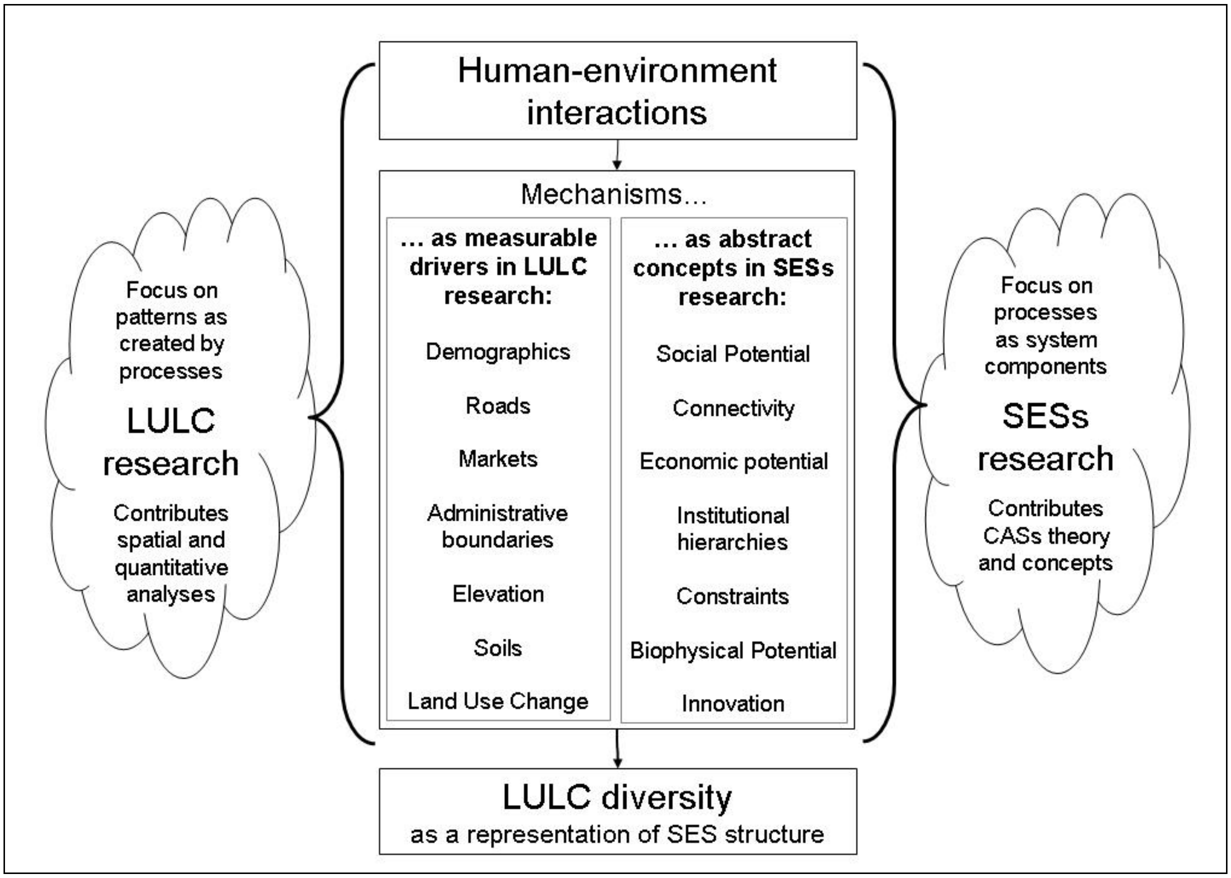


Figure 4-1. Schematic diagram showing how the divergent SESs and LULCC approaches to the study of human-environment interactions can be linked. The quantitative analyses used in LULCC research call for measurable drivers, or mechanisms, while those used to describe change in SESs draw explanations from generalized abstractions. LULC diversity is the proposed link, since it combines a generalized CAS concept with a quantifiable landscape characteristic.

The CASs approach underpinning SESs research emphasizes the dynamism and change inherent in human-environment interactions (Berkes and Folke 1998). The key focus is on system resilience – that is, how systems persist and maintain identity as they move through a range of conditions and are subjected to a range of internal and external perturbations (Carpenter et al. 2001; Holling 1973). The concept of SES resilience is built on the explicit recognition of such systems as being complex and adaptive (Holling 2001; Janssen, Anderies, and Ostrom

2007; Levin 1999; Walker and Abel 2002). The empirical, spatially explicit approach of LULCC research allows for the spatial and temporal location of the system to be analyzed (see Figure 4-1). With the increasing abilities of the applications of technologies such as remote sensing and geographic information systems (GIS), researchers can not only measure, but also map and model change and dynamism in LULC (Briassoulis 2000; Irwin and Geoghegan 2001; Manson 2005; Mas et al. 2004; Parker et al. 2003; Rogan and Chen 2004; Stibig, Beuchle, and Achard 2003; Verburg et al. 2002; Wessels et al. 2004; Wulder et al. 2007). The responses of landscape patterns to both local, proximate drivers and larger, more regional factors help researchers understand spatial variability (Lausch and Herzog 2002; Turner, Gardner, and O'Neill 2001; Wood and Porro 2002). Here we test whether LULC diversity responds to these drivers, so that this generalized concept can be used to compare conditions in a range of landscapes.

Diversity is a good place to start, since it is the most fundamental CAS characteristic, providing the complexity of components and range of responses required for adaptation (Levin 1999). Diversity is also readily applicable to LULC research. The spatial arrangement and distribution of different LULC types define a landscape's diversity. Further, landscape heterogeneity is a familiar concept, and the spatial metrics of diversity derived by landscape ecologists are increasingly being adopted by LULCC researchers (Cadenasso, Pickett, and Schwartz 2007; Lausch and Herzog 2002; Nagendra, Munroe, and Southworth 2004).

Research questions

The patterns of LULC diversity are useful to both LULCC and SESs research because they describe the system as expressed on the landscape and provide generalized information to allow cross-site comparison (Chapter 3). LULC diversity patterns should respond to the same mechanisms that are known to affect spatial and temporal variation in the distribution of individual LULC types. The way in which LULC diversity relates to these mechanisms provides important information on the state of the SES.

As suggested in Chapter 2, we can hypothesize about the relationships between LULC diversity and different mechanisms by assessing how the range of LULC types varies spatially. For example, we expect LULC diversity to be low very close to roads, then increasing sharply within accessible distance to the road, before decreasing steadily (Figure 4-2). We base this expectation on how household-level strategies play out collectively. For example, beyond easy foot access, human influence decreases and mainly natural vegetation is found. This means that the dominant crop (which in most subsistence communities is the most important LULC type) would be found along rural roads – to the general exclusion of other types. Further from the road, subsistence crops are interspersed with less frequently visited areas such as long-term tree crops, pastures, as well as a range of disturbed and undisturbed natural vegetation. Beyond easy foot access, human influence decreases and mainly natural vegetation is found. Likewise, right in the vicinity of the market, households activities will relate mainly to residence and the most important crop, and the number of LULC types will be low. Diversity will increase strongly with distance, since immediately beyond the residential areas householders will have a range of activities that are supported by market demands. At some point access becomes a limiting factor to the viability of market-influenced LULC types, so that LULC diversity tails off with increasing distance. We hypothesize that close to markets built areas will dominate the landscape, surrounded immediately by only the most important commercial crop, while further out commercial crops become interspersed with increasing areas of subsistence crops and a range of natural vegetation types. As with roads, as human influence drops off, natural vegetation will dominate the landscape (Figure 4-2). We suggest that the distribution of LULC diversity with increasing elevation will start off with intermediate magnitudes in low areas, increasing steadily with increasing elevation until steepness and rockiness causes a sudden drop-off in the number of LULC types. Lower areas are more accessible, and will be dominated by the main subsistence crop. With increasing elevation, changes in soil and slope make other crops more viable, so subsistence crops are interspersed with a range of tree crops and other commercial crops, as well as natural vegetation. At higher altitudes limited access and thin soils make agriculture less viable, so that only undisturbed natural vegetation is found (Figure 4-2).

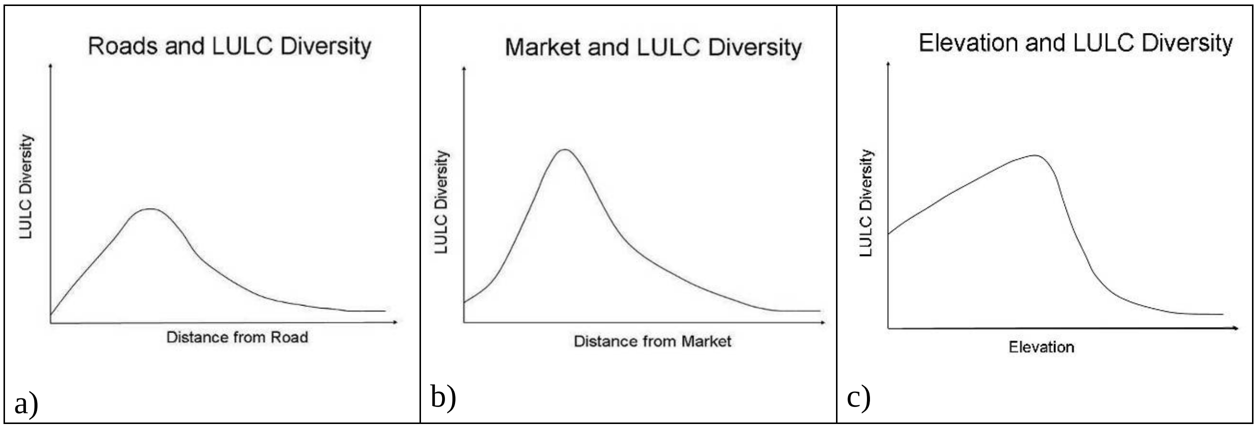


Figure 4-2. Hypothesized relationships between LULC diversity and a) distance to roads, b) distance to market, and c) elevation.

We pose the following questions to test whether these hypotheses correctly identify the nature of these relationships:

- How does LULC diversity change with distance to roads, distance to markets, and elevation?
- How do the general relationships between LULC diversity and these factors vary at different scales?
- To what extent does the actual distribution of LULC diversity agree with that predicted by models describing the hypothesized relationship?

Study Area

Cross-border studies provide an excellent opportunity for the comparative study of differences in the processes behind LULCC change (Bürgi, Hersperger, and Schneeberger 2004). This study tests the utility of the LULC diversity concept in the neighboring provinces of

Sisaket, Thailand and Ordar Mean Chey, Cambodia, in an analysis of change over a 16-year period from 1989 to 2005. The two provinces currently have highly dissimilar landscape configurations (Figure 4-3). We consider the two landscapes to represent the SESs of the two provinces, with the system processes represented by the patterns of four 14-category classifications (Figure 4-4) of Landsat TM and ETM+ imagery from seasonally comparable dates (see Chapter 3). The 14 classes, as described in Chapter 3, were identified using data collected on extensive field visits in 2005 and 2006, comparisons with related projects, and earlier maps (Blasco, Bellan, and Lacaze 1997; Mekong River Commission 2003; Nang Rong Projects 2004).

A low escarpment, dropping from Thailand into Cambodia, separates the two provinces. As a result of uplift, the plateau drains north into Thailand, resulting in hydrological separation.

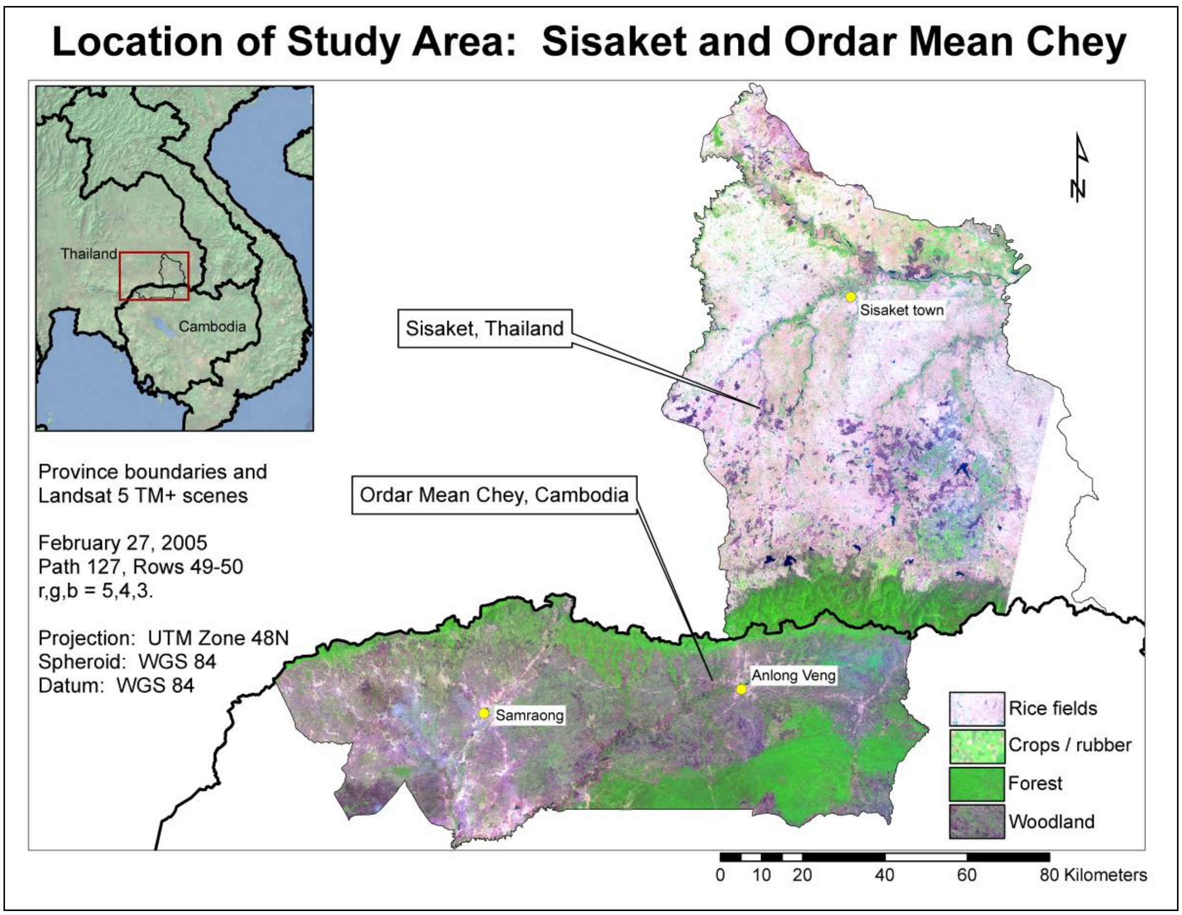


Figure 4-3. Study area map showing the different spectral characteristics of Sisaket, Thailand and Ordar Mean Chey, Cambodia

Sisaket and Ordar Mean Chey share general edaphic, geomorphological and climatic characteristics. Both are for the most part flat. A few large rivers cross them, and both were originally covered with semi-deciduous moist tropical forest. They both lie within the Asian monsoonal tropics, and have pronounced, five- to seven-month, rainy seasons. Currently, however, the provinces have very different landscape configurations, the consequence of different social, cultural, political and economic histories (Chandler 2000; Wyatt 1984). In addition, Cambodia's internal struggles since the 1970s have deepened its isolation from the rest of the world.

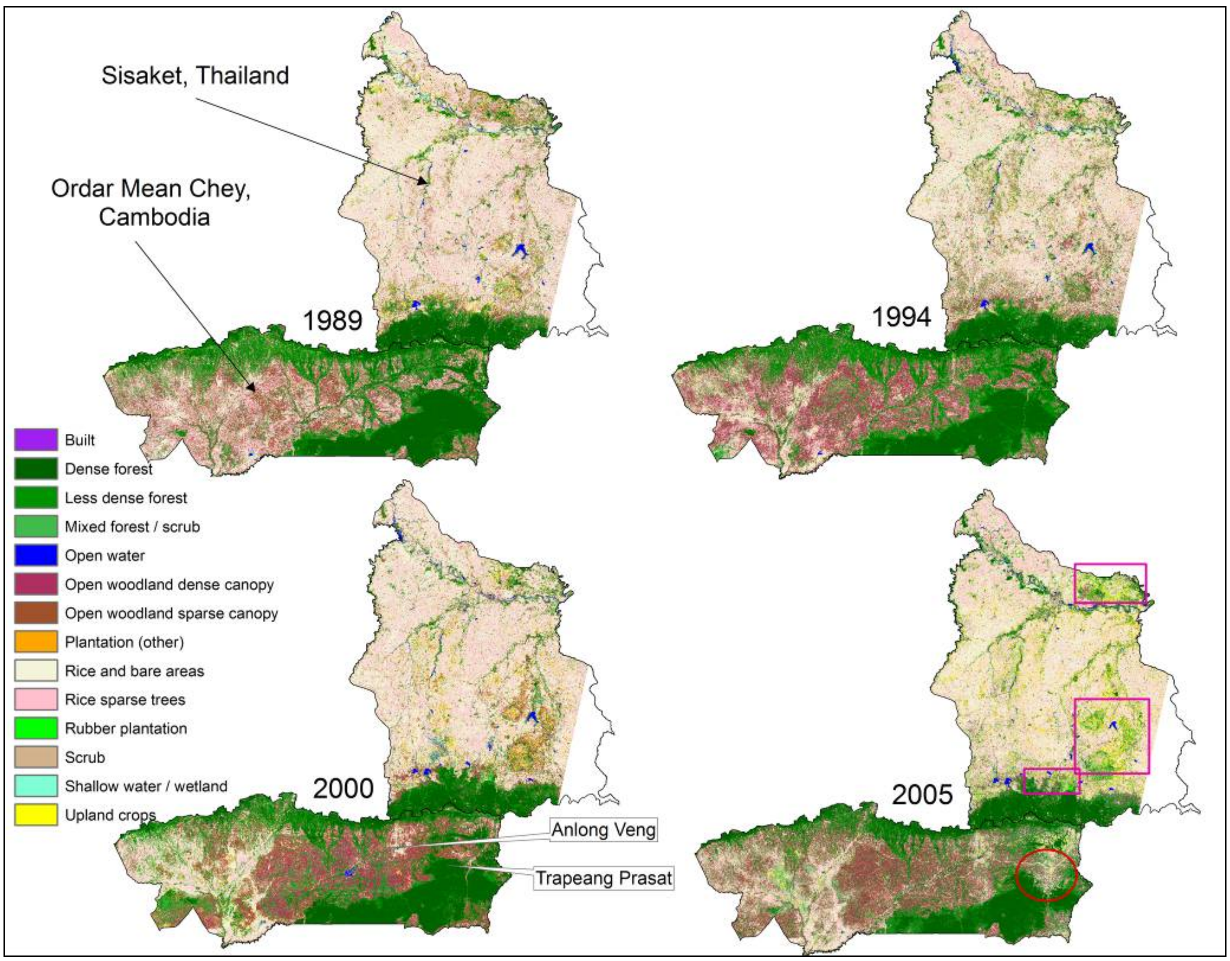


Figure 4-4. LULC classifications for Sisaket, Thailand and Ordar Mean Chey, Cambodia at each time-step in the study period. The circle on the 2005 classification shows the location of the wedge of deforestation in Ordar Mean Chey, while the rectangles highlight Sisaket's extreme north-east, escarpment foothills and three hilly areas, where woodland has given way to upland crops and rubber plantations.

Sisaket's predominantly agrarian landscape is defined by a dense hub-and-spoke network of mostly paved roads that radiate through a vast expanse of rice fields. Services are good, and all villages have electricity, piped water, and access to health and education facilities. Ordar Mean Chey, in contrast, had no paved roads during the study period.[5] Because this province was the last holdout of the Khmer Rouge guerrillas, it remained inaccessible to the national government until only recently. As a result, living conditions are very poor. There is no piped water, no mains electricity, and only a few larger villages have schools and clinics (Chapter 3).

As Figure 4-4 shows, Sisaket's landscape is dominated by extensive areas of rice fields traversed by a few large rivers. The rice cultivation areas, and the forested southern escarpment, have changed little during the study period. More locally, some dynamism in the SES is evident in the change in LULC in the far north-east, the three hilly areas to the south-east, and in the foot-hills of the forested escarpment. These areas have transitioned between woodland, upland crops, and increasingly, rubber plantations.

The influence of intensive agriculture evident in Sisaket's landscape provides a marked contrast to that of Ordar Mean Chey. Much of the rice production areas visible in the west of the Cambodian province in 1989 are, according to oral histories, collective farms that collapsed somewhat by 1994 due to ongoing internal conflict between the Khmer Rouge guerrillas and the new government. Areas of woodland expanded with land abandonment, presumably in part due to the presence of land mines. After 1994 the western part of Ordar Mean Chey stabilized, leading to the re-emergence of rice areas. By 2000, the village of Anlong Veng (visible as a small zone of rice around a reservoir due south of Sisaket's western border) expanded as this part of the province became the last hold-out of the Khmer Rouge. The eastern half of this province

[5] The first road was paved in late 2005 / early 2006.

then began to experience steady deforestation. A key development was the creation of a track through the south-eastern forest block in 1994 that opened up the area and led to the expansion of agriculture around the village of Trapeang Prasat. This is visible as a dramatic wedge of rapid deforestation between 2000 and 2005.

Methods

Development of Datasets

This spatially explicit study compares the landscapes underlying the two SESs, as described by the classifications shown in Figure 4-4 and discussed above. The 14 classes include several that fall on a continuum ranging from dense forest through less dense forest, dense canopy woodland, sparse canopy woodland, rice under sparse trees to treeless rice areas. The classification errors are in part a reflection of the somewhat arbitrary cut-off points imposed along this range (Table 4-1). The class “scrub / upland crops” was most difficult to separate from others. This is a result of the classifications being based solely on the spectral characteristics of the satellite imagery, which in some instances are very similar for different LULC classes. The accuracy assessment for the grouped classes resulted in an overall accuracy

Table 4-1. Error matrix and producer’s and user’s accuracy for accuracy assessment of 2005 classification based on 172 reference points

	Reference Data						
Classified Data	Water	Forest	Woodland	Rice	Scrub / Crop	Rubber	Built
Water	4	0	0	0	0	0	0
Forest	0	49	4	1	3	0	0
Woodland	0	0	6	0	2	0	0
Rice	0	1	2	77	7	0	0
Scrub / crop	0	3	1	0	6	1	0
Rubber	0	0	0	0	0	4	0
Built	0	0	0	0	0	0	1
% Producer’s Accuracy	100.0	92.5	46.2	98.7	33.3	80.0	100.0
% User’s Accuracy	100.0	86.0	75.0	88.5	54.6	100.0	100.0

of 85.5% and Kappa statistic of 0.779. These classifications are taken to be the starting point of this study.

We created raster-based maps of LULC diversity at three different scales by running moving windows of 3x3, 33x33, 303x303 pixels (Table 4-2) across the four initial classification images. The possible values of LULC variety range from a low of 1 to a high of 14 (because the classifications have 14 LULC types). The elevation map was derived from the 90 m Shuttle Radar Topography Mission digital topographic data, and resampled to 30 m using a bilinear interpolation approach to limit "steppiness" in the dataset.

Because road networks change over time, different 'distance to roads' maps were generated for each time-step. In both Sisaket and Ordar Mean Chey, most householders travel and transport their produce by motorcycle. Paved roads and unpaved tracks appeared to be equally accessible for most people, and were therefore treated as equal for this analysis. A substantial number of tracks for Ordar Mean Chey were recorded using a GPS receiver during fieldwork in 2005 and 2006. These were then overlaid over the satellite images for each year, and additional tracks were added or removed according to what was visible in each time-step, to create roads layers for each time-step. In Sisaket, highly detailed roads layers for 2004 were obtained from the Department of Highways and Department of Rural Roads. These were then adjusted according to the satellite imagery. Each time-step's roads layers were then buffered to create the 'distance to roads' maps.

Towns with markets were also identified during fieldwork. Although informal trade may also occur, for this study 'market' refers to permanent, managed infrastructure established for formal trade in locally grown produce. In Sisaket, a list was obtained from the provincial administration, while in Ordar Mean Chey, this information was obtained by visiting all three large villages. Each market was visited, so that geographic coordinates and dates of establishment could be verified. For each time-step, point files were made containing the markets that had been established by that time-step, and buffered to create 'distance to market' maps. Although straight-line distance does have some effect, most access to markets is along roads. Since both roads and markets showed change over time, we combined roads and markets to create 'cost-weight distance to market' maps by assigning 1 to roads and tracks, and 10 to all other surfaces as a simple order of magnitude weighting to constraining the *distance to markets* buffers.

Scale

The 30 m pixel resolution of the classifications is small enough to observe both the patterns in LULC diversity and the factors influencing LULCC, even at localized spatial extents (Chapter 3). At this resolution and with the smallest possible window-size (3x3 pixels) – as described below – variation at the micro-scale can be measured. In addition, this smallest window size corresponds roughly to 1 ha – the size of the finest scale of analysis (Table 4-2).

At 100 ha (corresponding to the community level of interest) enough pixels are present to capture all 14 possible LULC types and to reveal detailed spatial patterns of diversity. Because many social-ecological processes are scale-dependent (Allen and Starr 1982), we considered three scales of analysis, with the meso-scale of interest corresponding to the sphere of influence of the community (Table 4-2). For the purposes of this study, LULC diversity is assessed on the basis of variety – the number of types of LULC present at each scale.

Table 4-2. Scales of Analysis of LULC Diversity

	Micro-scale Contributing level	Meso-scale Level of interest	Macro-scale Constraining level
SES level	Household / farm	Community	District / province
Spatial extent	~ 1 Ha	~ 100 Ha	~ 100 Km^2
Analysis size	3x3 pixel window	33x33 pixel window	303x303 pixel window

Analysis

Data exploration showed that all of the variables had strongly non-normal distributions, and for this reason Spearman's rank correlations was used for initial assessment of the relationships. Because the datasets were very large (over 7 million cases), the statistical power is so strong that all relationships are significant with P-values less than 0.0001. In order to assess significance without using the P-values, we compared the correlation and F-test values themselves to the results of the same tests run on 20 different randomizations of the datasets. Since the randomizations had the same distribution as the actual tests, this process showed that the actual test values were not due to chance (Cumming 2004, Efron and Tibshirani 1993).

The Spearman's rank correlation is a good first step in determining whether LULC diversity responds to the same factors that affect individual LULC types, however, the relationship that the test measures is linear. The relationships predicted by the hypotheses are non-linear, and the correlation coefficients do not capture how the relationship varies with elevation or distance to roads and markets. The shape of the hypothesized curves (Figure 4-2) suggests instead a multiple-order polynomial relationship, which can be expressed in a general form for all three factors as:

$$ax^{(bx+cx^2)} + dx \qquad (1)$$

where:

y = predicted LULC diversity

x = the explanatory factor of interest (distance to roads, distance to market, or elevation)

and where the coefficients have the following effects:

a determines the initial values of the LULC diversity response, b influences the range of values in the first phase of the response curve,

c influences the range of values in the second phase of the response curve, and

d controls the function's sigmoidality by determining the angle of the tail.

This function was used to create maps of predicted micro-scale LULC diversity as a response to each of the three local-level explanatory factors. These predicted surfaces were then compared to the actual spatial distribution of micro-scale LULC diversity.

Random samples of 500 pixels per province (Figure 4-5) were used to generate coefficients for each explanatory factor in each province and at each time-step. The means, variances and distribution shapes for the samples were compared to those for the entire province datasets to verify that they were representative. The coefficients were identified by running the samples in LAB Fit, a curve-fitting analytical package (Silva and Silva 1999-2007) to establish how the

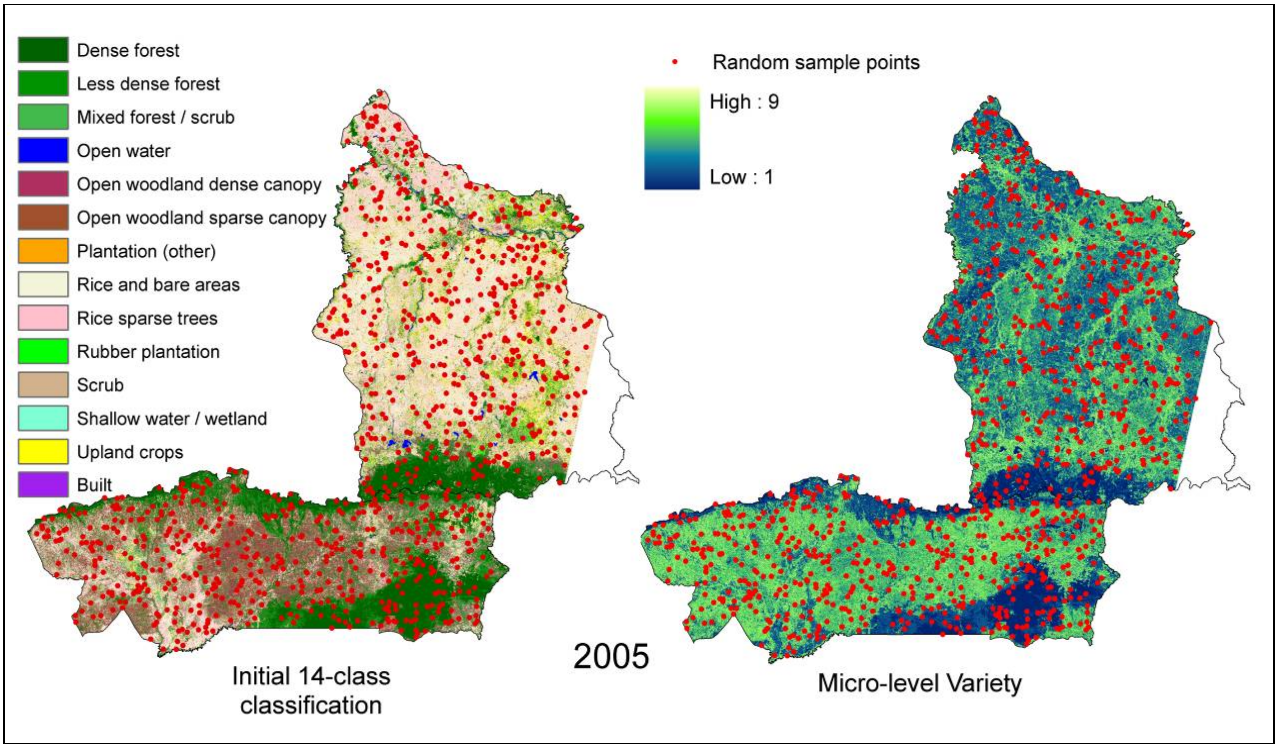


Figure 4-5. Distribution of 1000 random sample points (500 per province) shown relative to the 2005 classification and micro-scale LULC diversity.

actual LULC diversity values in the random samples responded to each explanatory factor within this function. The resultant coefficients were then applied to the maps of the explanatory factors using the function described above, to create maps predicting where LULC diversity would be located if that factor alone would influence its distribution. The predictive maps were then subtracted from the actual LULC diversity maps to determine:

a) how much of LULC diversity was explained by that factor,

b) in which locations the predictions were most accurate, and

c) whether or not the hypothesized shape of the relationship was generally correct.

Results

Spatial Distribution of LULC Diversity and Explanatory Variables

When compared to the classifications in Figure 4-4, the maps in Figure 4-6 show that the distribution of LULC diversity imitates the general patterns evident in the changing landscapes of the two provinces. In Sisaket, areas of high LULC variety follow the rivers, and depict the changing agriculture, along the escarpment foot-hills, and in the three hilly areas in the south-east. The provincial capital, Sisaket town, appears as a circle of high LULC variety in the north-centre of the map, just west of the large river junction.

In Ordar Mean Chey, the dense forests on the south-eastern hills stand out as areas of low LULC variety. The village of Anlong Veng is visible from 1994 onwards as a node of high diversity, with decreasing magnitudes radiating out from the settlement. The development of the road into the dramatic wedge of deforestation is clearly evident as first a line, and then a triangle of higher LULC variety cutting into the low LULC variety of the forested areas.

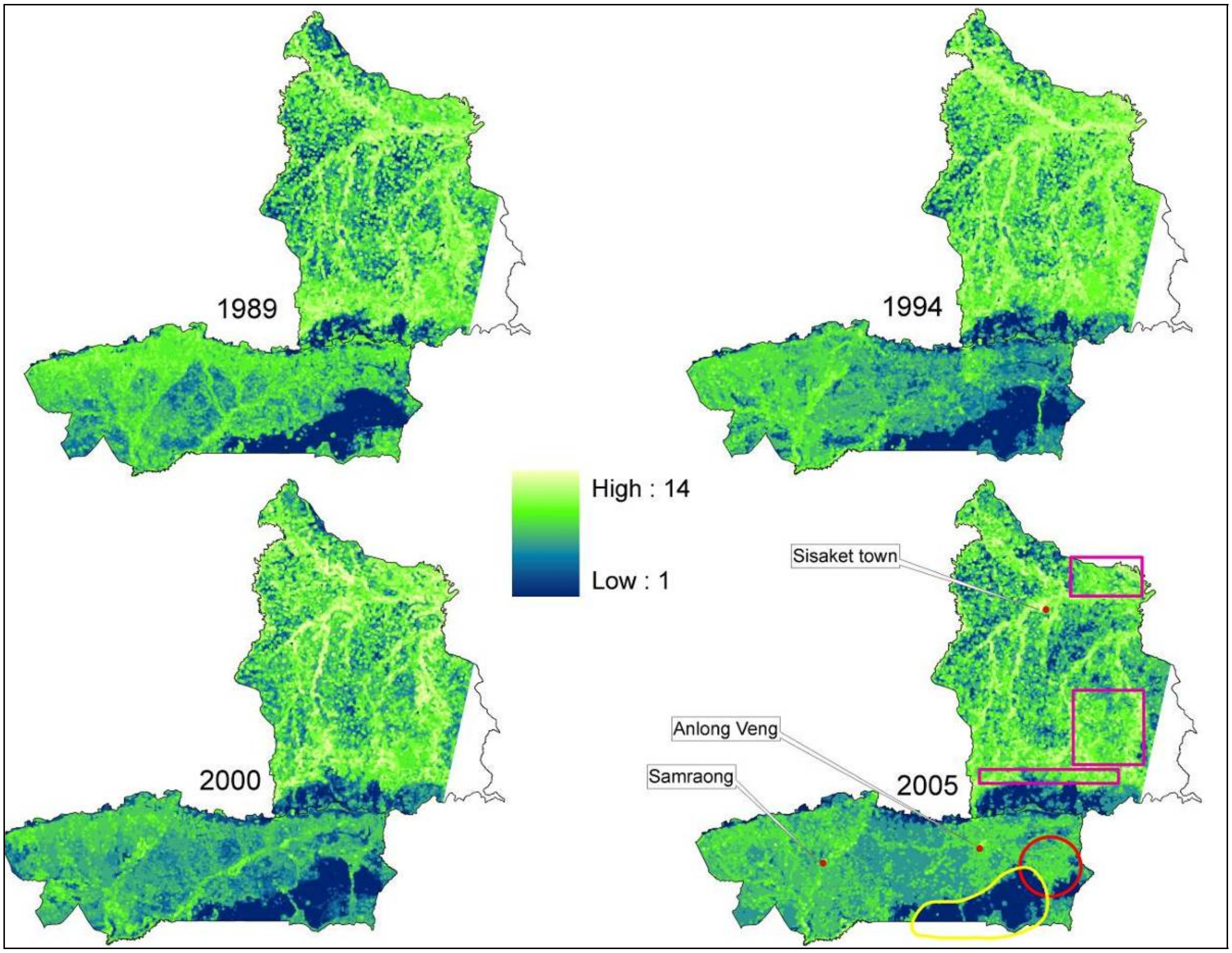


Figure 4-6. LULC variety at the meso-scale for 1989, 1994, 2000 and 2005. Distinct patterns can be followed across the landscape (see Chapter 3). The circle on the 2005 map shows the location of the wedge of deforestation in Ordar Mean Chey, while the freeform shows the low LULC diversity of the dense forests, and the rectangles highlight Sisaket's escarpment foothills and three hilly areas.

A comparison of LULC variety at the three different scales shows that the responses of LULC diversity to underlying biophysical and socioeconomic mechanisms present a smoother response at the meso-scale, allowing the dominant features to stand out (Figure 4-7). In addition, the influence of national context is clearly evident in the differences in LULC variety between the two provinces at the macro-scale, with the stronger global economic links in Thailand supporting the existence of a greater range of LULC types.

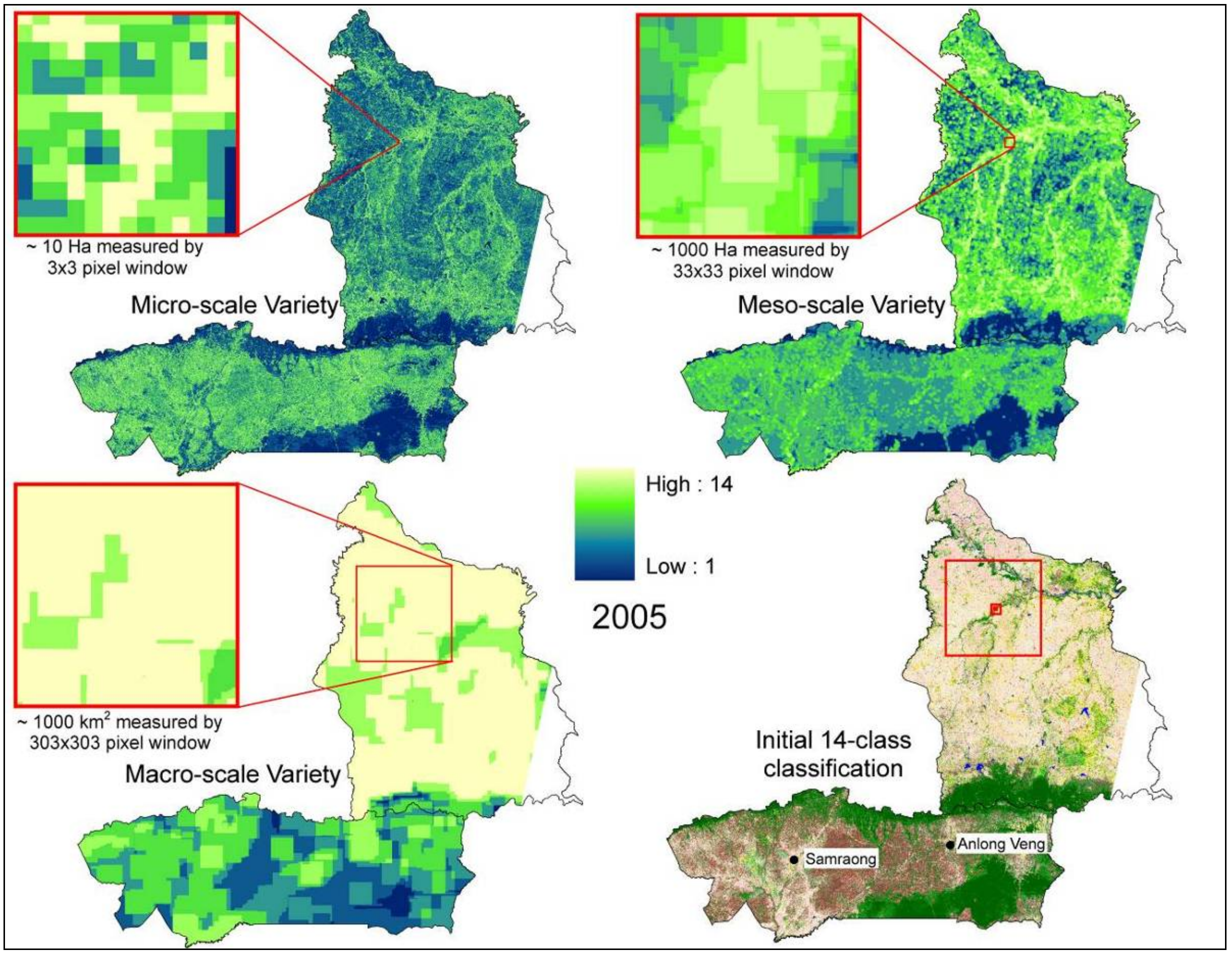


Figure 4-7. Spatial distribution of LULC variety in 2005, shown for the three different scales of analysis and in comparison to the initial classification. Each inset, centered on the same riparian area, shows a spatial extent representing roughly ten times the moving window size used for each scale, to show that the apparent differences are not simply a result of spatial zoom. At the micro-scale, patterns appear more random, while those at the macro-scale appear more uniform.

Infrastructural conditions are markedly different in the two SESs. For instance, the road network in Sisaket makes the entire landscape highly connected (Figure 4-8). In 1989, the maximum distance to any road was 9.2 km, with a median distance of 200 m. With little room for further road expansion, this median distance remained unchanged through to 2005. In Ordar Mean Chey, not only the number of roads, but also the location of some tracks changed, as is common of dirt tracks in undeveloped areas with low input from government. In 1989, the median distance to road was 1.2 km, with the greatest distance being 18.2 km. By 2005 the median and maximum distances had roughly halved to 0.8 km and 9.7 km respectively.

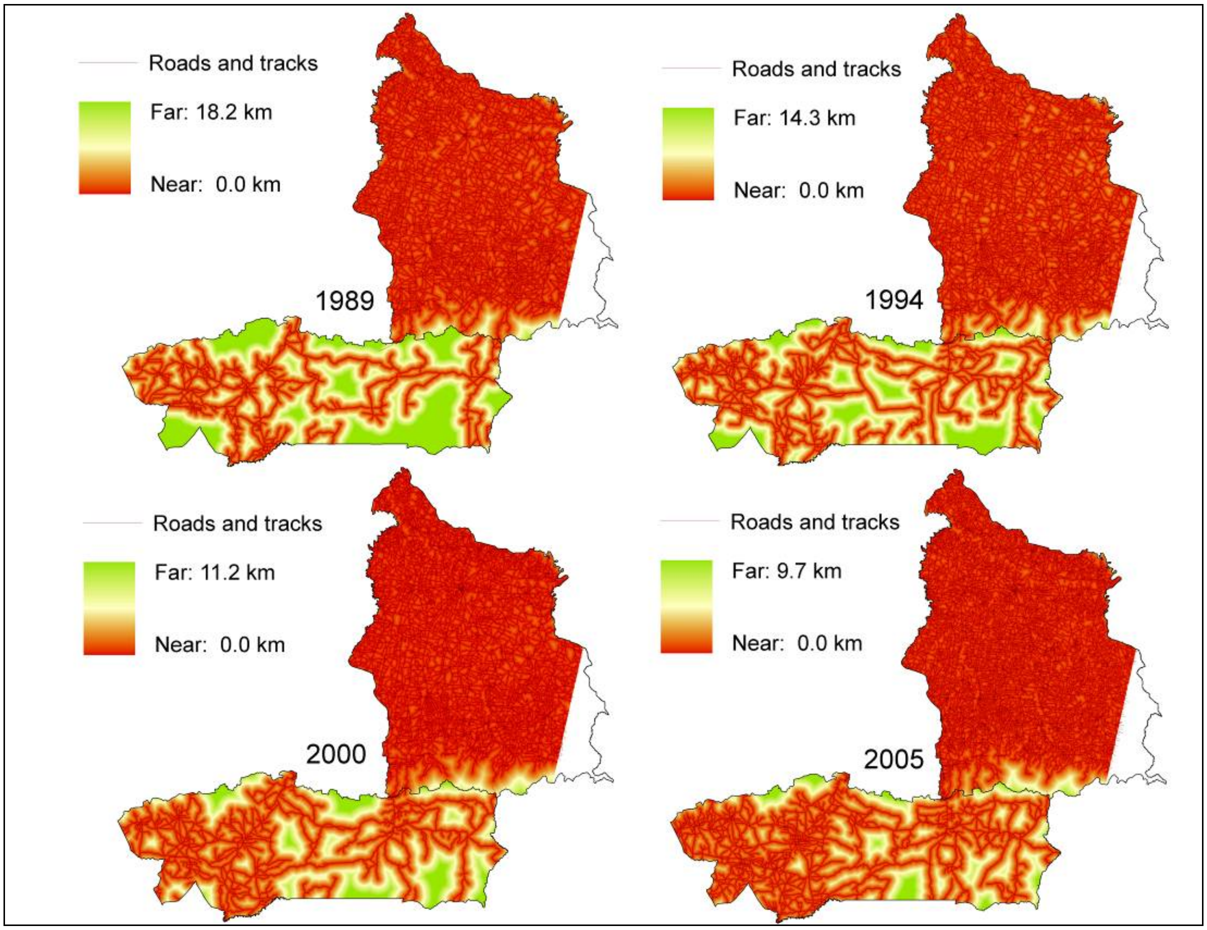


Figure 4-8. Distance to roads in 1989, 1994, 2000 and 2005

In Sisaket, based on date of establishment, the number of markets selling farmers' produce increased from four in 1989 to fourteen by 2005. Since the road network was well-established throughout the study period, it was the markets themselves that most changed the cost-weight distance to market across time (Figure 4-9). In Ordar Mean Chey, even though no new markets had been established by 1994, access was improved through the development of new tracks.

With the establishment of a market in Anlong Veng in 1999, and another in Trapeang Prasat in 2004, the cost-weight distance to market was greatly reduced in the eastern part of the province. However, to some extent the eastern and western halves of the province each retain stronger links to the rest of the country to the south than they do to each other. The roads from Samraong to Siem Reap (a major town south of the study area), and Anlong Veng to Siem Reap, are better established than that linking Samraong to Anlong Veng.

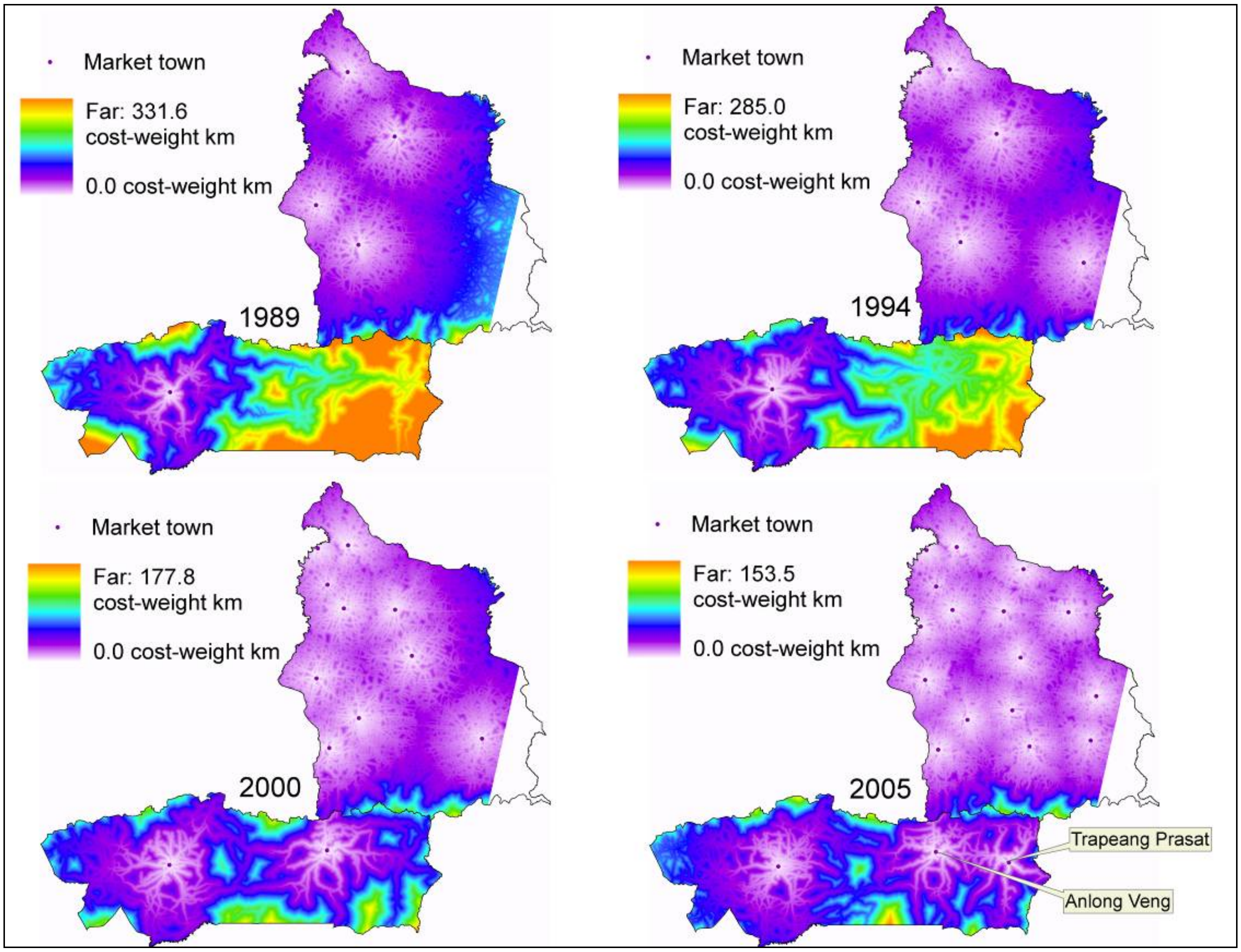


Figure 4-9. Cost-weight distance to market in 1989, 1994, 2000 and 2005

Although Sisaket sits on a plateau above Ordar Mean Chey, the difference between their mean elevations is only about 90 m (Figure 4-10). Ordar Mean Chey has a median elevation of 70 m, while that of Sisaket is 141.5 m. There is some overlap in the spatial distributions of all of the explanatory factors discussed here. In Sisaket, roads and markets are located only on the lower, flatter areas, and not in the higher, mountainous areas. In Ordar Mean Chey, there has been more change in the relationships. At the start of the study period, settlement and related infrastructure were located in the lower western part of the province, with hills (other than the steep escarpment) found in the east. However, over time roads and settlements have expanded into this slightly more elevated area.

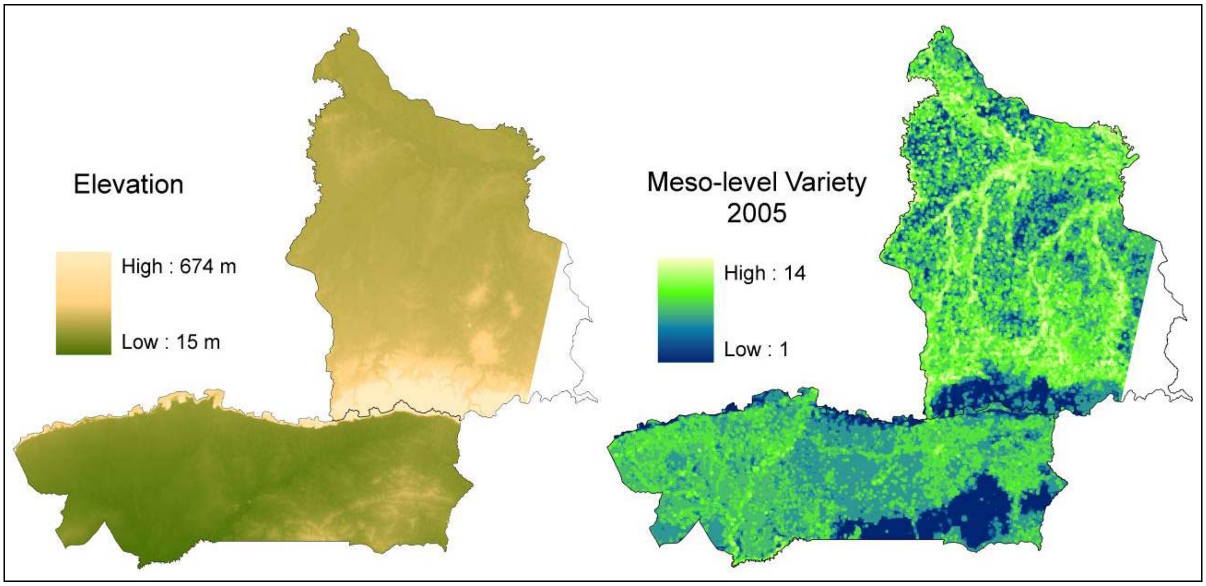


Figure 4-10. Elevation in the study area shown together with meso-scale LULC diversity in 2005.

Distance to Roads and LULC Diversity

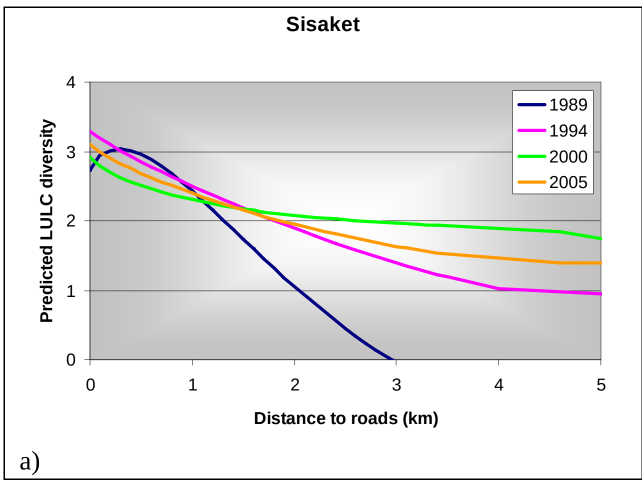
A comparison of the Spearman's correlation coefficients for LULC diversity and distance to road shows that, overall, Ordar Mean Chey has a much stronger response to distance to roads at all scales, reflecting the difference in road densities between the two provinces (Table 4-3 and Figure 4-8). The negative signs indicate that increasing distance to roads is associated with a decreasing magnitude of LULC diversity at all scales. In both provinces there is a general increase in the strength of the relationship over time at all scales, although this increase is not

Table 4-3. Spearman's correlation coefficients showing LULC diversity in response to distance to roads at each time-step

	Sisaket				Ordar Mean Chey			
	1989	1994	2000	2005	1989	1994	2000	2005
Micro-scale	-0.118	-0.158	-0.191	-0.194	-0.275	-0.203	-0.237	-0.271
Meso-scale	-0.149	-0.238	-0.289	-0.162	-0.263	-0.318	-0.356	-0.400
Macro-scale	-0.098	-0.047	-0.022	-0.167	-0.182	-0.122	-0.392	-0.277

always constant. In both provinces, the correlations are strongest at the meso-scale, suggesting that it is at this scale that the dominant patterns emerge on the landscape (Figure 4-7). However, at this broader scale interactions with other mechanisms are stronger, making it more difficult to model the specific nature of the relationship between LULC diversity and distance to roads.

The extent to which the actual relationships match the hypothesized shape in Figure 4-2a can be seen in Figure 4-11, which shows the predicted response of micro-scale LULC diversity to distance to roads for each time-step for the random sample of 500 points. In Sisaket, only 1989 shows the predicted initial increase, before LULC diversity magnitudes drop off with increasing distance. From 1994 onwards, conditions have changed substantially, suggesting that the actual relationship differs from that hypothesized, with a more linear decrease in diversity with increasing distance to roads. In Ordar Mean Chey a similar shift is observed, but only from 2000 onwards. This delay relative to Sisaket shows the extent to which Ordar Mean Chey lags behind that province in terms of infrastructural development. That both provinces experience this same change toward a more linear relationship suggests that over time, the system is



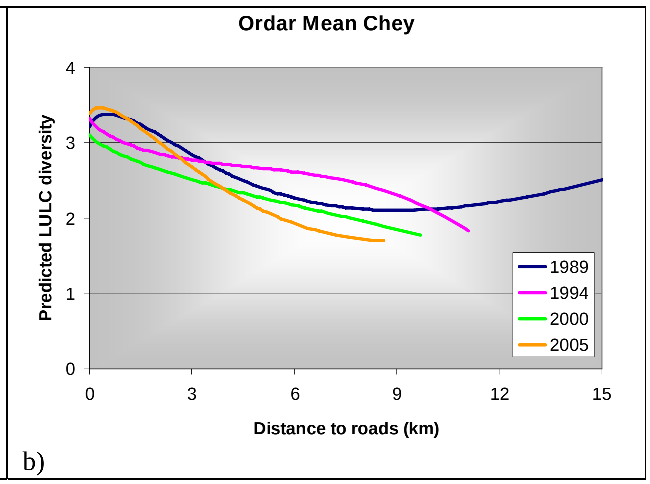


Figure 4-11. Predicted LULC diversity at the micro-scale in response to distance to roads in the function $ax^{(bx+cx^2)} + dx$ for four different points in time in a) Sisaket, and b) Ordar Mean Chey, based on the random sample with n=500, and using the coefficients generated from modeling the relationship with actual LULC diversity values. Coefficients for the models are given in Table 4-4.

Table 4-4. Coefficients used to predict LULC diversity at four time-steps in Sisaket and Ordar Mean Chey in response to distance to roads in the function $ax^{(bx+cx^2)} + dx$.

Sisaket	a	b	c	d
1989	2.717	-3.828E-01	6.080E-03	-2.879E-01
1994	3.291	3.356E-02	2.364E-03	-7.883E-01
2000	2.913	1.053E-01	-8.528E-03	-6.072E-01
2005	3.097	5.607E-02	1.319E-04	-6.996E-01
Ordar Mean Chey	a	b	c	d
1989	3.217	-8.988E-02	3.291E-03	1.256E-01
1994	3.329	4.197E-02	-2.140E-03	-3.231E-01
2000	3.099	2.335E-02	-7.881E-04	-2.692E-01
2005	3.385	-7.609E-02	5.548E-03	-3.469E-02

Table 4-5. Results of the models predicting LULC diversity in response to distance to roads showing goodness-of-fit, proportion of landscape variance explained by the model, mean difference and standard deviation between predicted and actual LULC diversity for the entire landscapes, and proportion of landscape where predicted LULC diversity is equal to or less than 1 type different from actual LULC diversity.

	X_r^2	Adj. R^2	Mean difference between actual and predicted LULC diversity	Standard deviation of difference between actual and predicted LULC diversity	% of landscape with difference less than 1 between actual and predicted LULC diversity
Sisaket					
1989	1.370	0.022	0.04	1.44	51.51
1994	1.692	0.062	0.15	1.42	48.46
2000	1.289	0.035	0.27	1.35	49.67
2005	1.660	0.034	0.21	1.38	56.62
Ordar Mean Chey					
1989	1.637	0.098	-0.09	1.30	48.92
1994	1.853	0.022	-0.04	1.33	50.22
2000	1.528	0.041	-0.03	1.19	55.81
2005	1.943	0.070	0.05	1.41	49.13

adapting as decreasing distance to roads allows households to change their livelihood strategies. Although the good fits for all of the province/years show that LULC diversity does respond to distance to roads, as expected this factor alone does not explain much of the variance in micro-scale LULC diversity when the function is applied to the entire landscapes (Table 4-5 and Figure 4-12) – with the adjusted R-squared values for Sisaket being particularly low. This implies that while LULC diversity does respond to distance to roads, in the province, roads are no longer a major determinant in the distribution of LULC diversity. In both provinces, however, the models predict LULC diversity to within one type across about 50% of the landscape (Table 4-5). In Sisaket the models marginally under-predicted the overall LULC diversity, as is shown by the mean differences between actual and predicted, whereas in Ordar Mean Chey – excepting 2005 – the models slightly over-predicted LULC diversity (Table 4-5).

The over- and under- predicted areas on the maps provide important information on what the other factors contributing to the distribution of LULC diversity are. For example, it is clear

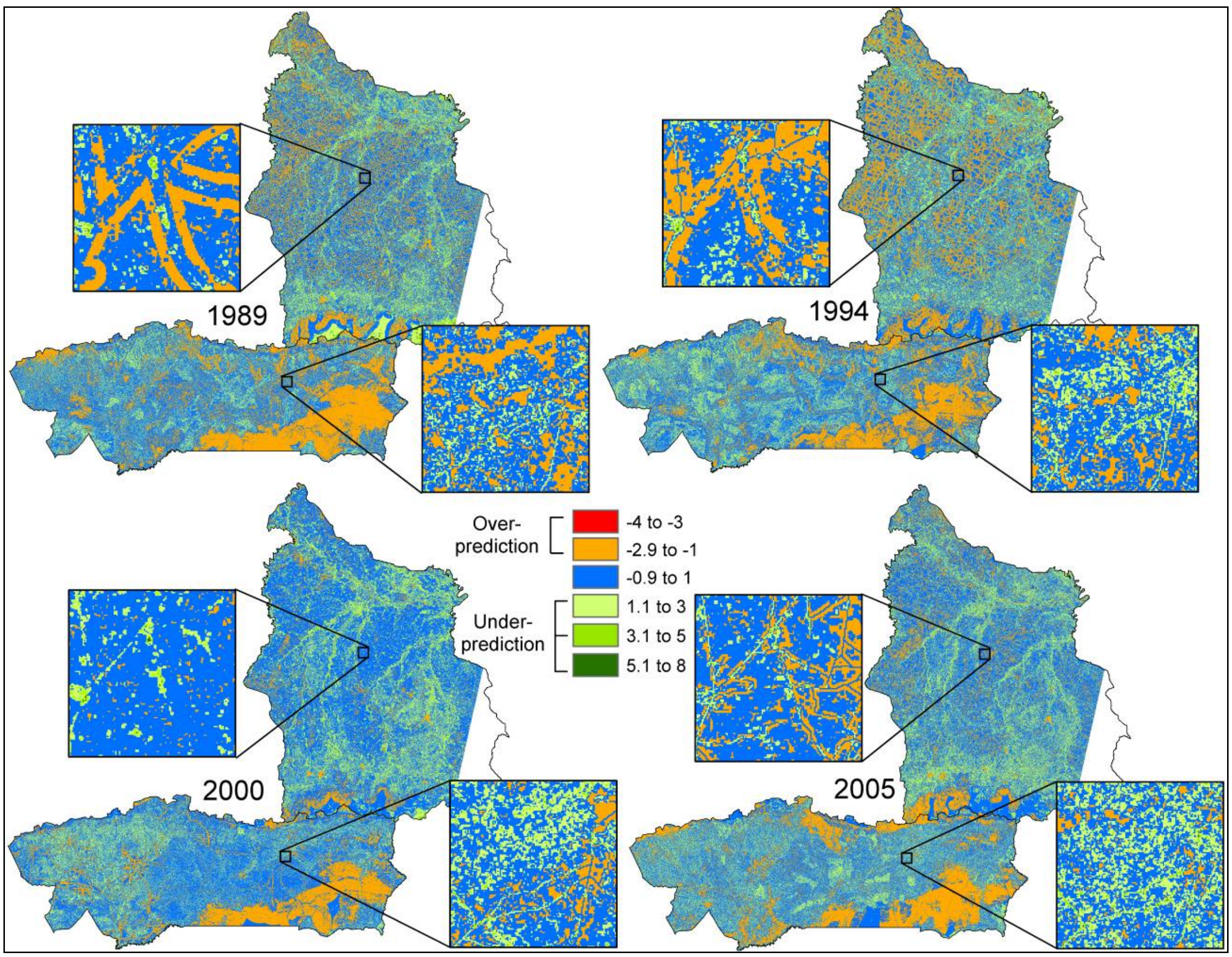


Figure 4-12. Residual map showing the difference between actual LULC diversity and that predicted by distance to roads in the function $ax^{(bx+cx^2)} + dx$. Orange to red areas show where the model over-predicts LULC diversity, and pale to dark green areas show where the model under-predicts LULC diversity. Insets show arbitrary locations of roughly 4 km x 4 km to give an indication of the distribution of the residuals when displayed at a finer map-scale.

that at all time-steps in Sisaket, rivers are areas of high LULC diversity independent of the influence of distance to roads (Figure 4-12). The inset for Sisaket in 1989 shows that while diversity is correctly predicted immediately next to the road, from about 100 m's distance it is over-predicted for the next 250 m as is shown by the distinctive bands paralleling the roads. The residual maps for 2000 and 2005 suggest that the more linear relationship depicted for these years in Figure 4-11 is a better description of this province's relation to diversity than that hypothesized in Figure 4-2a. Given the density of the road network in Sisaket (Figure 4-8), the fact that distance to roads does not play a major role in explaining the total variation in LULC diversity across the province's landscape is not surprising.

For Ordar Mean Chey, the most striking feature of the residual maps is how the distance-to-roads models over-predict for more elevated areas, adding weight to the hypothesis that elevation is also an important factor influencing LULC diversity. Over time, however, as roads penetrate into the hillier east of the province, the spatial extent of this over-prediction decreases (Figure 4-12). Rivers do not appear to have the same influence on LULC diversity in Ordar Mean Chey as they do in Sisaket.

Distance to Markets and LULC Diversity

The Spearman's rank correlation coefficients show that cost-weight distance to market is an important determination of the overall magnitude of LULC diversity (Table 4-6). This is particularly true in Ordar Mean Chey. As with distance to roads, the general trend is for a decrease in magnitude of LULC diversity with increasing cost-weight distance to market. The anomalous positive correlations for Sisaket in 1989 can be attributed to the lack of a market to the south-east of the province until 1994 (Figure 4-9), in spite of the presence of the 3 hilly areas of fertile soil and high LULC diversity highlighted in Figure 4-4. Unlike distance to roads, there is no single scale at which the correlations are strongest – instead this varies from year to year.

In Ordar Mean Chey, there is a considerable decrease in correlation strength in 2000 at the micro- and meso-scales, but a strong increase at the macro-scale. This relates to the addition of the province's second market, in Anlong Veng (Figure 4-9), which reduced the influence of the Samraong market at the micro- and meso-scales, and created more evenly distributed access for the entire landscape.

Table 4-6. Spearman's correlation coefficients showing LULC diversity in response to cost-weight distance to markets at each time-step

	Sisaket				Ordar Mean Chey			
	1989	1994	2000	2005	1989	1994	2000	2005
Micro-scale	0.028	-0.067	-0.262	-0.086	-0.426	-0.422	-0.262	-0.264
Meso-scale	0.026	-0.147	-0.126	-0.130	-0.361	-0.598	-0.290	-0.386
Macro-scale	-0.068	-0.083	-0.271	-0.144	-0.120	-0.098	-0.394	-0.267

In Sisaket there has been greater variability over time in cost-weight distance to market compared to distance to roads, and this is reflected in the changing shapes of the models using this factor to predict LULC diversity (Figure 4-13). In all years there is an initial increase before magnitudes drop off with increasing distance, yet not to the degree suggested by the hypothesized curve (Figure 4-2b). The change in Ordar Mean Chey has been more dramatic.

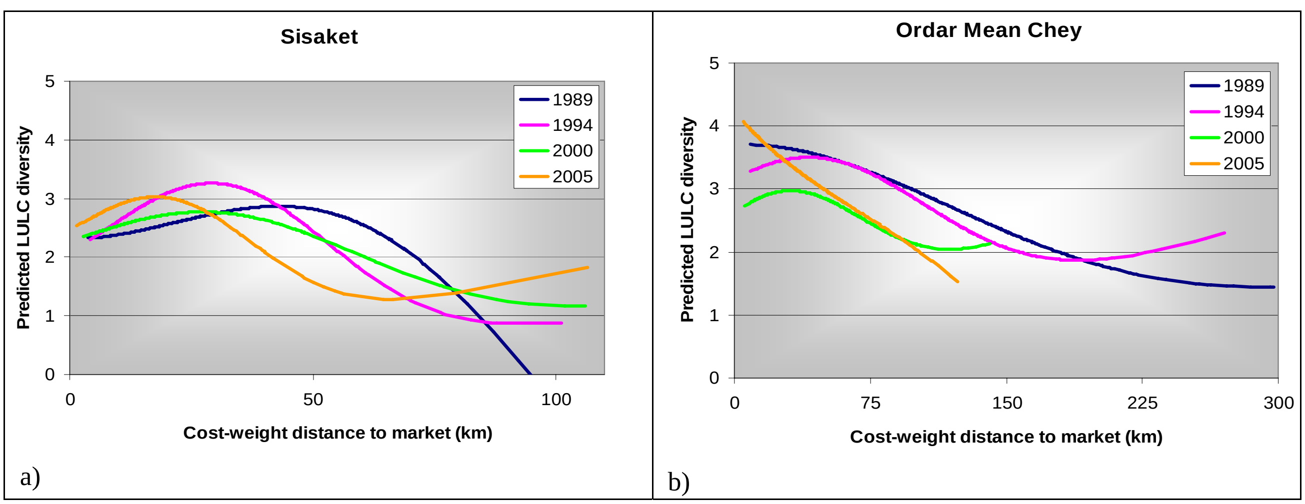


Figure 4-13. Predicted LULC diversity at the micro-scale in response to cost-weight distance to market in the function $ax^{(bx+cx^2)} + dx$ for four different points in time in a) Sisaket, and b) Ordar Mean Chey, based on the random sample with n=500, and using the coefficients generated from modeling the relationship with actual LULC diversity values. Coefficients for the models are given in Table 4-7.

Table 4-7. Coefficients used to predict LULC diversity at four time-steps in Sisaket and Ordar Mean Chey in response to cost-weight distance to market in the function $ax^{(bx+cx^2)} + dx$.

Sisaket	a	b	c	d
1989	2.377	6.037E-03	-5.834E-05	-3.114E-02
1994	2.164	8.572E-03	-1.784E-04	8.439E-03
2000	2.307	3.280E-03	-8.693E-05	9.842E-03
2005	2.511	6.005E-03	-2.485E-04	1.714E-02
Ordar Mean Chey	**a**	**b**	**c**	**d**
1989	3.695	-3.440E-04	-4.613E-06	4.189E-03
1994	3.173	6.445E-04	-1.655E-05	8.457E-03
2000	2.643	7.095E-04	-3.604E-05	1.428E-02
2005	4.282	1.627E-03	-4.586E-06	-5.288E-02

Table 4-8. Results of the models predicting LULC diversity in response to cost-weight distance to market showing goodness-of-fit, proportion of landscape variance explained by the model, mean difference and standard deviation between predicted and actual LULC diversity for the entire landscapes, and proportion of landscape where predicted LULC diversity is equal to or less than 1 type different from actual LULC diversity.

	X_r^2	Adj. R^2	Mean difference between actual and predicted LULC diversity	Standard deviation of difference between actual and predicted LULC diversity	% of landscape with difference less than 1 between actual and predicted LULC diversity
Sisaket					
1989	1.335	0.044	0.18	1.34	63.47
1994	1.647	0.087	0.06	1.33	50.32
2000	1.289	0.027	0.19	1.27	63.97
2005	1.647	0.042	0.07	1.26	56.30
Ordar Mean Chey					
1989	1.410	0.222	-0.09	1.21	56.03
1994	1.584	0.162	-0.05	1.21	55.88
2000	1.522	0.044	-0.04	1.16	56.88
2005	1.912	0.085	0.01	1.37	49.21

Since there was only one market in the province in 1989 and 1994, the addition of a yet another by 2000 almost halved the effective distance to market for the eastern part of the province (Figure 4-9 and Figure 4-13b). By 2005 both the increase in road density and the addition of a third market have seen the response of LULC diversity change to being almost linear. These shifts could be qualitatively interpreted as representing adaptations in the SES state, particularly at the local level.

As with those based on distance to roads, the models predicting LULC diversity based on cost-weight distance to market generally under-predicted LULC diversity in the Sisaket landscape and over-predicted for Ordar Mean Chey (Table 4-8). For the most part, cost-weight distance to market better predicts diversity than distance to roads alone, producing models for which 50 to 64% percent of the landscape is predicted to within one LULC type (Table 4-8 and Figure 4-14). The adjusted R-squared values show that in Ordar Mean Chey in 1989 and 1994, market proximity, as a single variable, explained much of the variation in LULC diversity

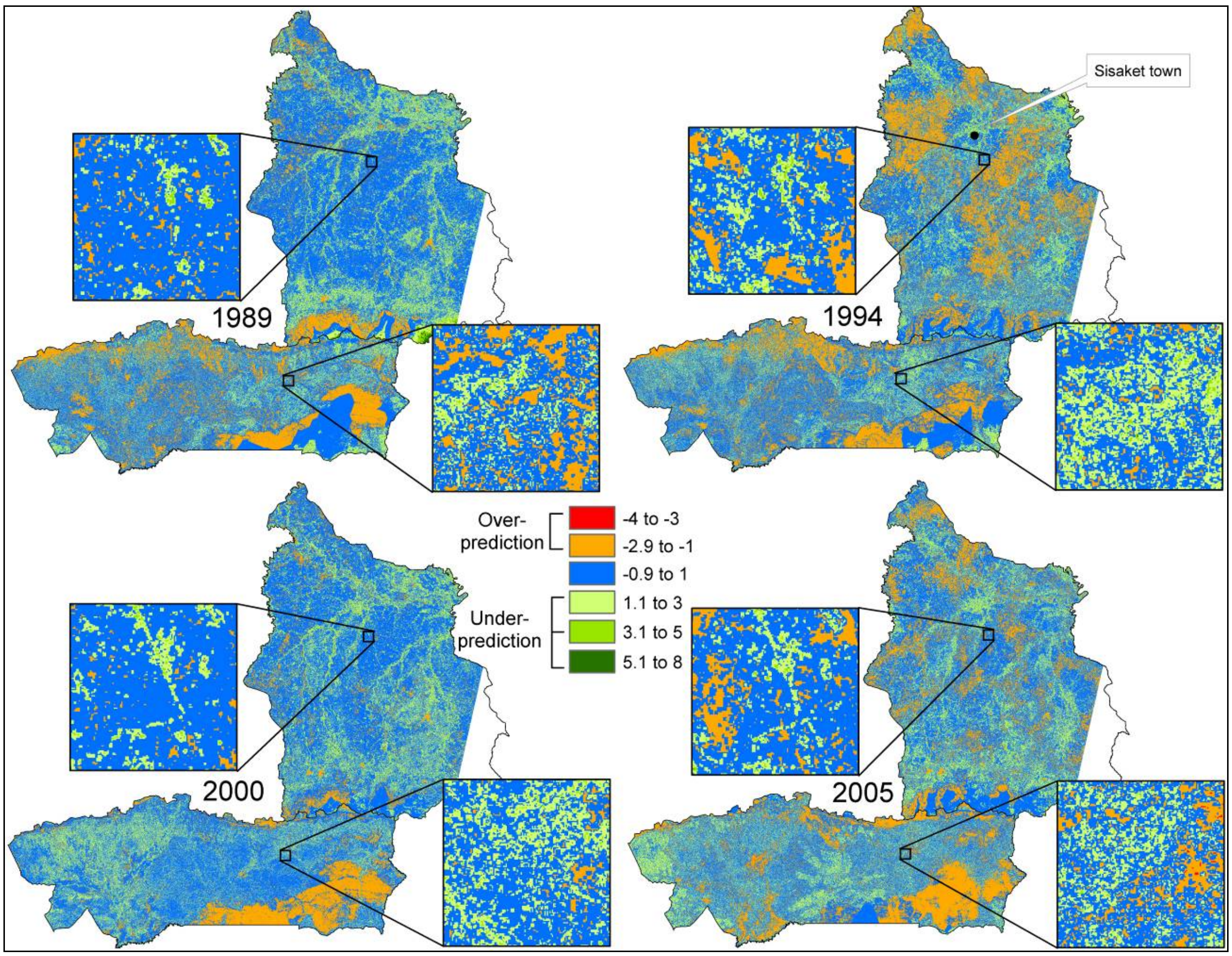


Figure 4-14. Residual map showing the difference between actual LULC diversity and that predicted by cost-weight distance to market in the function $ax^{(bx+cx^2)} + dx$. Orange to red areas show where the model over-predicts LULC diversity, and pale to dark green areas show where the model under-predicts LULC diversity. Insets show arbitrary locations of roughly 4 km x 4 km to give an indication of the distribution of the residuals when displayed at a finer map-scale.

magnitudes across that province's landscape (Table 4-8), and the spatial extent of the over-prediction associated with the hilly south-east is reduced, relative to the models for distance to roads (Figure 4-14). These market models have tended to over-predict LULC diversity in the west of the province for all but 2000 (Figure 4-14). In Sisaket, the low adjusted R-squared values again suggest that this province is so highly connected in infrastructural terms that other factors now play a larger role in explaining the spatial distribution of LULC diversity. For example, rivers are again visible as areas for which LULC diversity is under-predicted, as is the area around Sisaket town from 1994 onwards. The 1994 Sisaket map shows large areas of over-predicted diversity, and this model had the lowest total predicted area within 1 type of the actual LULC diversity (Figure 4-14 and Table 4-8).

Elevation and LULC Diversity

Spearman's rank correlation coefficients show that for the whole landscapes, there is a general decrease in the number of LULC types with increasing elevation at all scales (Table 4-9). Again, the relationships are stronger in the less-developed province of Ordar Mean Chey than they are in Sisaket. There is some variability in the scale at which the relationship is strongest at the different time-steps, however, in Sisaket for the most part it appears weakest at the micro-scale, possibly because this linear measurement masks the fact that, at this fine scale, higher LULC diversity is associated with intermediate elevation – with lowest areas dominated by rice, and highest areas dominated by forest (Figure 4-4). In contrast, strong relationships are found at

Table 4-9. Spearman's correlation coefficients showing LULC diversity in response to elevation at each time-step

	Sisaket				Ordar Mean Chey			
	1989	**1994**	**2000**	**2005**	**1989**	**1994**	**2000**	**2005**
Micro-scale	-0.023	-0.028	-0.033	-0.037	-0.422	-0.427	-0.335	-0.378
Meso-scale	-0.088	-0.243	-0.260	-0.127	-0.196	-0.473	-0.358	-0.329
Macro-scale	-0.165	-0.090	-0.306	-0.194	-0.067	-0.035	-0.321	-0.373

the micro-scale in Ordar Mean Chey at all time-steps (Table 4-9), possibly because much of the human-induced change in this province is still taking place in the lower areas to the west of the province (Figure 4-4).

Because elevation does not change over time, we expect less variation in the relation between this factor and micro-scale LULC diversity compared to the relation to roads and markets, and the graphs in Figure 4-15 show that this is indeed the case. For all time-steps, the shapes of the Sisaket LULC diversity models based on elevation resemble the hypothesized shape (Figure 4-2c) more closely than those of the other factors. The model shapes for Ordar Mean Chey present more abrupt changes with increasing elevation, and also show a second increase in LULC diversity after the initial strong decrease, from about 200 m elevation onwards. This is probably because the eastern half of the province is higher than the western half while still being relatively flat, so that multiple LULC types can emerge (Figure 4-10). Overall LULC diversity in the eastern half is generally lower because this area has had limited settlement because of the area's political history.

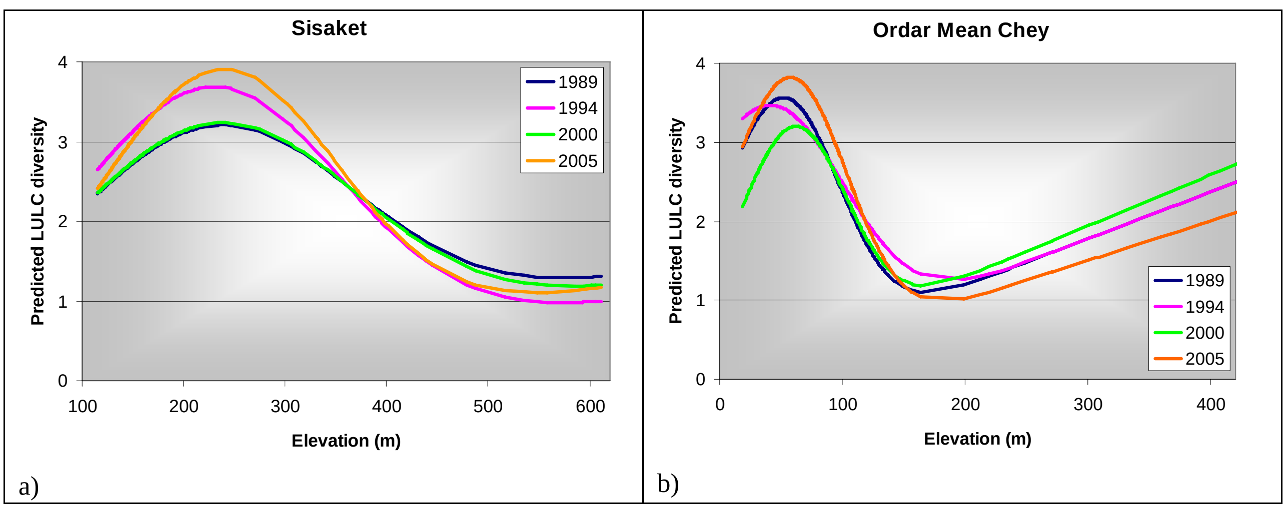


Figure 4-15. Predicted LULC diversity at the micro-scale in response to elevation in the function $ax^{(bx+cx^2)} + dx$ for four different points in time in a) Sisaket, and b) Ordar Mean Chey, based on the random sample with n=500, and using the coefficients generated from modeling the relationship with actual LULC diversity values. Coefficients for the models are given in Table 4-10.

Table 4-10. Coefficients used to predict LULC diversity in response to elevation in the function $ax^{(bx+cx^2)} + dx$.

Sisaket	a	b	c	d
1989	1.112	1.626E-03	-3.947E-06	2.058E-03
1994	1.155	1.926E-03	-4.704E-06	1.588E-03
2000	1.116	1.647E-03	-3.961E-06	1.875E-03
2005	0.798	2.526E-03	-5.885E-06	1.891E-03
Ordar Mean Chey	a	b	c	d
1989	2.407	3.782E-03	-4.440E-05	5.932E-03
1994	3.028	1.408E-03	-2.426E-05	5.935E-03
2000	1.631	5.275E-03	-5.103E-05	6.475E-03
2005	2.377	4.163E-03	-4.281E-05	5.008E-03

Table 4-11. Results of the models predicting LULC diversity in response to elevation showing goodness-of-fit, proportion of landscape variance explained by the model, mean difference and standard deviation between predicted and actual LULC diversity for the entire landscapes, and proportion of landscape where predicted LULC diversity is equal to or less than 1 type different from actual LULC diversity

	X_r^2	Adj. R^2	Mean difference between actual and predicted LULC diversity	Standard deviation of difference between actual and predicted LULC diversity	% of landscape with difference less than 1 between actual and predicted LULC diversity
Sisaket					
1989	1.322	0.056	0.11	1.26	66.50
1994	1.632	0.096	0.05	1.29	56.11
2000	1.239	0.066	0.17	1.27	64.28
2005	1.515	0.116	0.06	1.25	59.66
Ordar Mean Chey					
1989	1.384	0.226	-0.12	1.18	59.63
1994	1.600	0.141	0.70	1.24	58.68
2000	1.422	0.112	-0.08	1.11	61.10
2005	1.615	0.228	-0.02	1.26	55.61

Not only does elevation most closely match the hypothesized response of LULC diversity, but it also predicts most accurately the spatial distribution of distribution of LULC diversity, with between 55 and 66% of the landscape being predicted to within one LULC type in all time-steps and both provinces (Table 4-11 and Figure 4-16). In Ordar Mean Chey, elevation as a single factor accounts for a lot of the overall variance in the landscape, as is shown by the adjusted R-squared values. As with distance to roads and cost-weight distance to market, most of the under-predicted areas in Sisaket relate to riparian features, again highlighting their importance in determining the distribution of LULC diversity in this province (Figure 4-16). In Ordar Mean Chey in 1994 extensive areas in the north-western part of the province, which are slightly elevated, are under-predicted, and this is reflected in the mean difference between actual and predicted LULC diversity (Table 4-11), which shows that this year's model performed poorly relative to the other years. In contrast, the under-predictions in 2005 relate to the dramatic wedge of deforestation described in Figure 4-4. The residual maps of the elevation-based models for Ordar Mean Chey (Figure 4-16) show that the hilly south-eastern area is well-

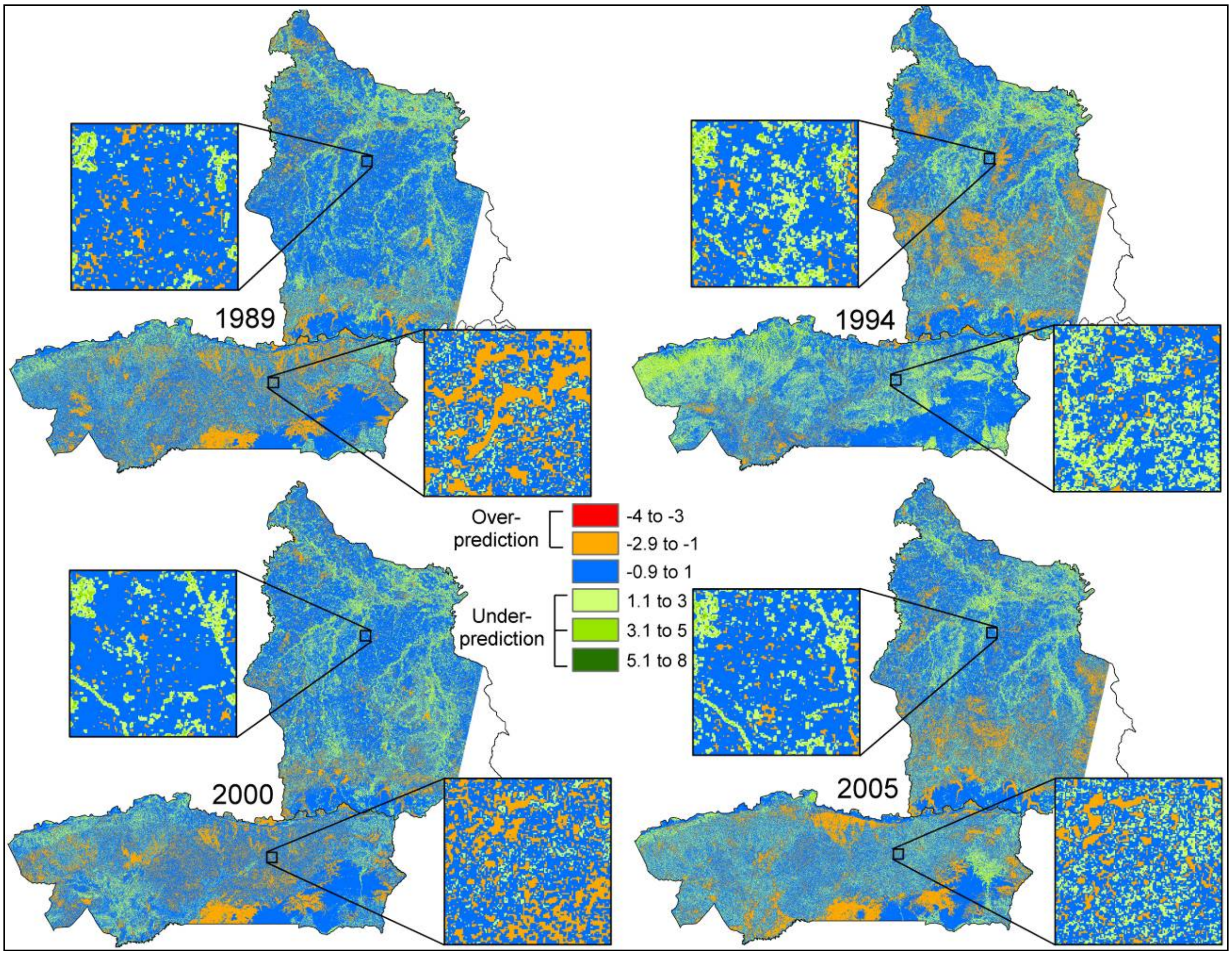


Figure 4-16. Residual map showing the difference between actual LULC diversity and that predicted by elevation in the function $ax^{(bx+cx^2)} + dx$. Orange to red areas show where the model over-predicts LULC diversity, and pale to dark green areas show where the model under-predicts LULC diversity. Insets show arbitrary locations of roughly 4 km x 4 km to give an indication of the distribution of the residuals when displayed at a finer map-scale.

predicted, with errors to the north and west. This is in contrast to the roads- and market-based models, which performed better in the north and south, and over-predicted for the hilly south-east (Figure 4-12 and Figure 4-14). This suggests that a model that combined cost-weight distance to market (which includes the influence of roads) and elevation might explain much of the variance in Ordar Mean Chey.

Discussion

Overall, magnitudes of LULC diversity are higher in Sisaket than in Ordar Mean Chey. Likewise, this province clearly has a greater degree of infrastructural development. This means that not only do the SESs have different potential responses, but also differences in the factors affecting the responses. Variations at different time-steps in the relationships with the distance to roads and market variables are to some extent due to changes in these explanatory variables. This does not diminish the importance of the changing LULC diversity values, but instead highlights the importance of other system attributes, such as the connectivity of the SESs. For example, the weaker relationships in Sisaket between LULC diversity and roads and markets suggest a higher degree of connectivity and rigidity to that SES, where human influence has reached a point where it limits the system ability to respond to these factors (Carpenter, Ludwig, and Brock 1999; Holling and Gunderson 2002). This suggests that the strength of the relationship between LULC diversity and various underlying mechanisms could be explored as an indicator of the sustainability of the SES.

Roads clearly play a key role in determining the distribution of micro-scale LULC diversity – however, not in the form hypothesized. Although the qualitative shape of the hypothesis was not supported by the models, there is nevertheless an overall decline in LULC diversity with increasing distance to roads, and LULC diversity is shown to be affected by accessibility in the same way as change in individual LULC types. In Sisaket, the road network is so dense that in this small-holder agrarian system, one is never more than three or four fields away from a road. With the exception of the border escarpment, the low LULC diversity associated with greatest distance from road is related to the dominance of the main subsistence crop – rice, and not undisturbed natural vegetation. Given that nearly all land is within ready access by road, it appears that close to roads, more economically attractive land uses that tend to cover smaller areas, such as residences, cash crops and plantations, combined with the diversity associated with road verges (scrub and ephemeral surface water) mean that in Sisaket LULC diversity is highest close to the road. In Ordar Mean Chey, even though people may mainly be planting the dominant subsistence crop close to the road, the linear settlement pattern means that here too, diversity is high close to the road, as people tend to have cash and tree crops around their homes, while far from the road, as expected, LULC types tend to be restricted to the dominant natural vegetation. This means that the relationship between distance to roads and LULC diversity may be better expressed as a linear decline with increasing distance. Although the specific nature of the hypothesized relationship was not borne out, nevertheless the data show that LULC diversity is affected by the spatial distribution of roads.

While the hypothesized graph for changes in LULC diversity with cost-weight distance to market suggested large and abrupt change with initial increases in distance, the data show that this trend is more gradual. Nevertheless, the models still show the initial increase in LULC diversity with increasing distance, followed by a decrease, described by the hypothesized left-skewed, inverted U distribution. In Sisaket, the uneven spatial distribution of markets in the earlier years influenced the nature of their relationship to LULC diversity, drawing attention to the issue of feedbacks. As markets became more evenly distributed across the province, the relation to LULC diversity took on a shape closer to that hypothesized, raising the question of how much markets affect LULC diversity and how much they are affected by it.

While road densities in Sisaket change little over the study period so that access to market was influenced more by changes in the distribution in markets, in Ordar Mean Chey, changes in the roads and tracks played a large role in changing access to markets. The shape of the 1989 model reflects how many roads linked to a single market, and with an additional market in 2000, the model more closely resembles the hypothesized shape. By 2005, however, the addition of a third market in the frontier area of the eastern part of the province where abrupt change is taking place, means that the relationship in the last time-step was almost linear, with high diversity close to the newly established markets, declining sharply as human influence gave way to the densely forested areas.

Encompassed in the effect of elevation on LULC diversity are related factors such as slope and soil. This is most evident in Sisaket, where the three hilly areas of intermediate elevation in the south-east have high LULC diversity primarily because of the richer soils there, whereas the much higher escarpment mountains are very steeply sloped and rocky, limiting human access and use. The combination of these factors contributes to the way in which the models conform to the hypothesized shape. In Ordar Mean Chey politics have limited the ability of humans to expand their influence into the gently sloped hills of the eastern part of the province, so that at all time-steps in the study period there is an abrupt increase and then decrease in the number of different LULC types within a relatively small elevation range. In the future, as the east of the province opens up, we might expect this transition to be more gradual.

The areas of over-prediction in the residual maps for cost-weight distance to market (which incorporates the effect of roads) and elevation clearly show that complementary information is contained in the prediction models based on each of these variables. It would therefore be useful to identify a model that combined cost-weight distance to market (which incorporates the effect of roads) with elevation, as together they would likely explain much of the variance in the spatial distribution of LULC diversity.

While the models explored here describe the nature of the responses for LULC diversity at the micro-scale only, it is clear from the Spearman's rank correlations that the effect of these local-level drivers can nevertheless also be felt at broader scales. However, at each higher scale of analysis, a larger area is incorporated in the assessment of diversity, which increases the influences and interactions of other processes, making it hard to identify how each variable individually affects LULC diversity at these broader scales. To understand better the distribution of LULC diversity at the meso- and macro-scales, however, it is more important to identify factors that contribute to patterns at these broader scales (Levin 1992). For example, the maps suggest that rivers may be a major underlying mechanism controlling LULC diversity distribution at the meso-scale. The more fertile soils and access to water in riparian areas not only create a greater range of natural LULC types (Naiman and Decamps 1997), but also provide the conditions for a range of LULC types – more than individual households could account for, but which collectively a community or village would likely generate. Likewise, a broad-scale mechanism such as degree of integration in the global economy might influence the range of human-dominated LULC types and so better explain macro-scale LULC diversity.

This study shows that at the micro-scale the hypothesized relationships between LULC diversity and these factors were supported, with some modification to the exact nature of the relationship in the case of distance to roads. Even in the dissimilar systems that the study provinces represented, LULC diversity had the same general responses to factors known to influence LULCC. That is, increasing accessibility and infrastructural development led to increasing LULC diversity in much the same way that they lead to forest conversion and agricultural expansion; and higher elevations constrained LULC diversity just as they do the conversion of one specific type of LULC to several others (Chapter 2; Cropper, Puri, and Griffiths 2001; Bürgi, Hersperger, and Schneeberger 2004; Caldas et al. 2007; Chomitz and Gray 1996; Crews-Meyer 2004; Erenstein, Oswald, and Mahaman 2006; Etter et al. 2006; Messina et al. 2006).

The way in which LULC diversity relates to these mechanisms provides important information on the state of the SES. Variations in the responses of LULC diversity show that the SESs are adaptive, responding to the influence of the factors tested here. Weakening relationships suggest that a system is becoming more connected. The processes leading to the emergence of patterns on the landscape result from household-level decisions to national policies. Just as these processes are scale-dependent (Levin 1992), so too are the response patterns (Chapter 3). While the individual choices of farmers might appear as random when examined at the level at which they occur, their aggregate effect at the community level emerges as a pattern at a broader level. At the same time, the context provides a set of conditions that will impose limitations on the potential range of factors (Ahl and Allen 1996). For example, the degree to which a country is integrated into the global economy will determine the potential range of LULC types the provincial SES can include.

Conclusion

While LULC diversity provides a simple but useful generalization for cross-site comparison, predicting its response to different factors requires further development of the theory and the identification of factors more likely to influence spatial and temporal variation at the meso- and macro-scales. The use of CASs to frame the analysis of landscape change provides a means to integrate SESs research with LULCC research. LULC diversity links the metaphors that guide SES research to the more practical reality of how humans, as the dominant species, structure of the landscape. The effect of drivers of change on different landscapes can be compared by measuring the response of LULC diversity instead of the responses of individual LULC types which might otherwise be context-specific (Perz 2007). The condition of SESs can be expressed quantitatively by using LULC types as an expression of SES components. Linking LULCC and SES research allows a system's location in space and time, and at multiple scales, to be included in the evaluation of its past, present and future states.

CHAPTER 5
CONCLUSION

The broad goal of this dissertation has been to address the question of whether CASs theory and the concept of LULC diversity can help link SESs research and LULCC research, and in so doing provide the former with a way of measuring system change and the latter with generalizations for cross-site comparisons and deductive analysis. To this end, in this dissertation I set out to test whether it was possible to detect variation in LULC diversity across landscapes, whether this variation displayed some structure or organization in its distribution at different scales, and whether it was possible to attribute the distribution of LULC diversity to underlying biophysical and socio-economic mechanisms. These research problems were answered in the three separate research papers comprising this dissertation.

The first paper in this dissertation shows that linking LULCC and SESs research under the same theoretical framework is possible. LULCC, as expressed across landscapes, can be seen as a tangible expression of SES processes. The CASs concepts such as diversity that are explicit in the study of SESs have been implicit in many LULCC policy statements and case studies. The novel application of the CASs approach builds on known relationships between change in individual LULC types and various factors influencing that change. These interactions are used to predict the distribution patterns and responses of LULC diversity to these underlying system mechanisms. The paper explains how a spatially explicit approach using landscapes provides a way for quantifying components of SESs.

The second paper proves that LULC diversity does have spatial and distributional structure. LULC diversity patterns form distinct patterns on the landscape, which suggest the influence of rivers, mountains, roads and settlements. LULC diversity maintains similar frequency distributions across time, while the shape of the distributions is scale-dependent.

The third and final paper demonstrates that even in dissimilar SES landscapes, LULC diversity has the same general responses to underlying mechanisms. These responses vary with spatial scale, but there are distinct trends in the direction of the relationships – such as increasing magnitudes of LUC diversity with decreasing elevation, distance from roads and distance from markets. At the micro-scale, LULC diversity is shown to respond to elevation and distance to market in ways similar to those hypothesized – that is, an initial increase to higher magnitudes followed by decrease to lower magnitudes. However, the relationship to distance to roads was found to be more linear.

Significance of Findings

Together, these three papers contribute to the development of two emerging research programs – LULCC, and SESs. Firstly, the novel manner in which CASs theory and the concept of diversity are applied in this dissertation provides LULCC researchers with generalizations for comparison, extrapolation and prediction. This approach allows us to look at landscapes as LULC diversity can be tested and evaluated in any landscape, independent of the specific environmental and social characteristics. CASs theory should prove useful to researchers trying to move LULCC research from inductive towards deductive analysis (Rindfuss et al. 2004; Walker 2004), because it can be the source of predictive hypotheses that are neither context-specific nor discipline-dependent (Perz 2007). Trends in magnitudes of diversity can be inferred by drawing on the CASs ideas of selection, emergent properties, non-linearity, path dependency and scale, inter alia (Ahl and Allen 1996; Arthur 1999; Holland 1995; Kauffman 1995; Lansing 2003; Levin 1998).

Secondly, by explicitly treating LULC types as the expression of SES components, the approach developed here provides SESs researchers with the means to measure change in the system (Carpenter et al. 2001; Cumming et al. 2005). By using LULC diversity as a generalized unit of analysis in a SES, we can spatially represent change in the condition or state of any SES. We can then use change in LULC diversity to assess the likelihood of a SES changing or persisting in terms of its structure and function, since any change in the range of potential responses will affect the ability of a system to adapt and persist (Holland 1995; Levin 2003). The landscape approach also allows SESs research access to the well-developed methods used by LULCC scientists and landscape ecologists.

LULC Diversity

This research verifies the utility of LULC diversity as a generalization for comparing and contrasting different SESs. LULC diversity patterns not only incorporate and mirror the actual LULC types from which they are derived, but they also provide an indication of the degrees of intensification, fragmentation and diversification of the SES landscape (Bogaert, Farina, and Ceulemans 2005; Crawford et al. 2005). LULC diversity may have different overall magnitudes in different landscapes, and respond in different ways and at different points in time to similar biophysical and socioeconomic factors. However, the shapes of LULC frequency distributions are similar enough that these differences can be compared and contrasted, and lead to the conclusion that LULC diversity is a means to overcoming context-specificity (Perz 2007; Bürgi, Hersperger, and Schneeberger 2004).

As a quantifiable concept, LULC diversity offers distinct advantages over the standard classification approach to LULCC. Because the measures of diversity are discrete (variety) and continuous (relative abundance) as opposed to categorical, this increases the options for exploring spatial and temporal variability in a quantitative manner. LULC diversity provides a way to quantify SESs as expressed on the landscape, and can be used to measure system characteristics such as change and persistence (Carpenter et al. 2001; Cumming et al. 2005). In addition, because the LULCC approach is spatial, a focus on changes (or not) in LULC diversity reveal where system identity is changing or persisting.

Complex Adaptive Systems, LULCC, and SESs

As a theoretical construct, LULC diversity provides additional insight into the human-environment interactions that are shaping our world, particularly when considered through the framework of CASs. For example, LULC diversity shows different responses at different scales, reflecting the multi-scalar nature of SES processes (Ahl and Allen 1996). The spatial arrangement of LULC diversity suggests that SESs are self-organizing, with landscape patterns emerging from interactions with a complex array of mechanisms (Holland 1995; Levin 2005). Locally, magnitudes of diversity in some cases decrease as LULC types are winnowed away, and in other cases increase, as new types evolve (Levin 1999). The threshold-type response of LULC diversity change trajectories in places of high temporal variability is evidence that change in LULC diversity is non-linear, another characteristic of a complex, adaptive SES (Folke et al. 2004; Holland 1995; Holling and Gunderson 2002).

Further Work

The next step in the application of CASs to the study of human-environment interactions would be to test the concept of LULC diversity in other landscapes. It would be useful to have sufficient case studies to develop a general distribution curve for LULC diversity at different scales, against which individual scenarios can be assessed. Similarly, we need to explore whether the responses of LULC diversity to various underlying mechanisms hold up under other social-ecological conditions, such as in urban areas or savanna rangelands (Cadenasso, Pickett, and Schwartz 2007; Walker and Abel 2002).

The range of explanatory factors should be explored further to identify the best models explaining the distribution of LULC diversity (for each scale of analysis) in one type of landscape, and then to test whether the same model would work in different landscapes. This dissertation suggests that the relationships between LULC diversity and most underlying mechanisms are likely to be non-linear. Further attention is required to try to understand how and why the nature of the relationships varies. Because the underlying processes appear to be scale-dependent, different variables will need to be identified for inclusion in the models for each of the scales of analysis.

Additional CAS characteristics, such as connectivity, aggregation and path-dependency are regularly referred to in LULCC studies. Studies that specifically examine how change in LULC types can be captured by these characteristics should be pursued. The large differences in road density, combined with the differences in response of LULC diversity to distance to roads, in the two study provinces suggests that the role of connectivity in determining LULC diversity should be explored further. Likewise, the effects of aggregation require additional study, by experimenting with merged or grouped LULC categories. The effect of scale of analysis on scale of process would also benefit from further attention. For example, slight adjustments might increase the emergence of patterns, while larger grain sizes could reduce processing time while still revealing the same information. Although not always framed in the same terminology, many LULCC modelers recognize path-dependency in their systems of interest, and this work could be extended to focus on whether the probabilities of conversion of individual LULC types can be applied in a similar fashion to predict changes in magnitudes of LULC diversity.

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BIOGRAPHICAL SKETCH

Lin Cassidy was born in South Africa. She gained her Bachelor of Arts at the University of Cape Town, with a double major in French and sociology. She then completed a 1-year honors degree in French literature, before moving to Maun, Botswana in 1987. After working in the wildlife-based eco-tourism industry in the Okavango Delta for several years, she attended the University of Zimbabwe, where she obtained a Bachelor of Science special honors degree in sociology. Lin returned to Botswana where she has been working as a freelance consultant in rural development, mainly on short-term projects for donor organizations, NGOs, or government departments. Increasingly she has focused her work on the community-based natural resources management sector, with a particular interest in the areas surrounding the Okavango. In 2001 she became a naturalized Botswana citizen. Lin came to the University of Florida to learn more about the ecological aspects of natural resources management, and to pursue the links between social and ecological systems, and in 2003 obtained her Master of Science degree in interdisciplinary ecology. She completed her PhD in geography, with a minor in political ecology, through the University of Florida's Land Use and Environmental Change Institute and Department of Geography, before returning home to Botswana to continue working on issues relating to conservation and development, and people's reliance on natural resources and the environment.