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Global Land Project

Science Plan and Implementation Strategy

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Science Plan and Implementation Strategy

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Preface

The global environment is changing due to human and natural causes. The challenge of understanding global environmental change and of providing the policy-relevant knowledge base required by societies to deal with this change reaches across many aspects of scientific endeavour. Research combines observations, process studies, manipulative experiments and modelling, to improve the capability to explain and predict global environmental changes. Much of the international global change research is facilitated by four programmes, which in addition to the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) include DIVERSITAS (an international programme of biodiversity science) and the World Climate Research Programme (WCRP). The programme-specific and co-sponsored research projects of these four programmes, while retaining more focused disciplinary efforts, are increasingly evolving to tackle critical system-level questions that require a more integrated approach across disciplines and programmes.

The Global Land Project (GLP) Science Plan and Implementation Strategy represents the joint research agenda of IGBP and IHDP to improve the understanding of land system dynamics in the context of Earth System functioning. This plan is therefore a first critical step in addressing the interaction between people and their environments. It is part of the broader efforts to understand how these interactions have affected, and may yet affect, the sustainability of the terrestrial biosphere, and the two-way interactions and feedbacks between different land systems within the Earth System. GLP will play a clear role in improving the understanding of regional and global-scale land systems, as well as promoting strong scientific synergy across the global change programmes.

This Science Plan and Implementation Strategy sets out the research agenda for the next decade, based on credible, high quality science. It is intended primarily for researchers and potential sponsors, but also for the wider scientific community. One of the most important roles of GLP will be to work with the scientific community to build implementation strategies for international research that are scientifically effective and resource efficient. Many of the questions posed can best be answered by long-term coordinated efforts enabled by an international community. GLP networks will share expertise, thus contributing to an accelerating knowledge base on an emerging land systems science.

This Science Plan and Implementation Strategy develops a new integrated paradigm focused on two main conceptual aspects of the coupled system: firstly, it deals with the interface between people, biota, and natural resources of terrestrial systems, and secondly, it combines detailed regional studies with a global, comparative perspective. GLP takes as its points of departure ecosystem services and human decision making for the terrestrial environment. These topics are at the interface of the societal and the environmental domains, and serve as conceptual lenses for the research plan.

The Science Plan emphasises changes in the coupled socio-environmental system, and builds upon the extensive heritage of IGBP and IHDP global networks of scientists, data and largely disciplinary understanding, particularly from the IGBP project on Global Change and Terrestrial Ecosystems (GCTE) and from the joint IGBP-IHDP project on Land Use and Land-Cover Change (LUCC). The Science Plan also promotes new networks and addressing the coupled socio-environmental system at various scales.

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Chair IHDP Scientific Committee

Guy Brasseur
Chair IGBP Scientific Committee

September 2005

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This Science Plan and Implementation Strategy is the outcome of numerous meetings beginning with the "Terrestrial Futures Meeting" in Stockholm (Sweden) in December 2000, and followed by a meeting at the Max-Planck Institute of Atmospheric Chemistry (Mainz, Germany) in October 2001 where the boundary conditions of GLP and the IGBP Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) were first discussed. The GLP Transition Team was commissioned jointly by IGBP and IHDP in 2002. A series of subsequent meetings were held at the Natural Resource Ecology Laboratory, Colorado State University (Colorado, USA) in January 2002 and April 2003. An IHDP/IGBP co-sponsored meeting in Bilthoven (Netherlands) in October 2002 allowed IHDP and IGBP scientists to further contribute to the development of the science plan.

At the 2003 IGBP Congress, additional critical input, particularly from the IHDP Secretariat, provided the basis of the research framework, which was reviewed and discussed at the Land Open Science Conference in Morelia (Mexico) in December 2003. The expanded first draft the Science Plan and Implementation Strategy emerged from the working groups formed at the Open Science Conference, and was then further revised by the GLP Transition Team, with the assistance of Jill Lackett and Patti Orth. Finally, a GLP Advisory Team was appointed in May 2004 by IGBP and IHDP to improve the focus and balance of the document.

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Contents

Executive Summary

Human transformations of ecosystems and landscapes are the largest source of change on Earth, affecting the ability of the biosphere to sustain life. Humans have become ever more adept at appropriating and altering the Earth's resources for human needs. Intensification and diversification of land use and advances in technology have led to rapid changes in biogeochemical cycles, hydrologic processes and landscape dynamics. Changes in land use and management affect the states, properties and functions of ecosystems, which in turn, affect the provision of ecosystem services and hence human well-being. Furthermore, biophysical alterations and social forces generate different responses in the Northern Hemisphere than in the Southern Hemisphere, in urban environments than in rural environments, and in developed countries than in developing countries.

Links between decision making, ecosystem services and global environmental change define important pathways of feedback from coupled human-environment activities at the local and regional scale, and to and from the global scale. However, there is a need for greatly improved understanding of how human actions affect natural processes of the terrestrial biosphere, and an even greater need to evaluate the consequences of these changes.

The goal of GLP is therefore:

to measure, model and understand the coupled human-environmental system.

This goal is part of broader efforts to understand changes in the interaction between people and their environments, and the ways these have affected, and may yet affect, the sustainability of the Earth System. Changes in coupled human-environmental systems affect the cycling of energy, water, elements and biota at the global level, and global-level changes in political economy, such as international treaties and market liberalisation, affect decisions about resources at local and regional levels.

Understanding changes in the coupled human-environmental system is enhanced when directed to the level of ecosystems and their synergy with human agents and societal structures, including the human consequences of biophysical changes. GLP therefore focuses on the interactions of the people, biota and natural resources of terrestrial and freshwater systems at local to regional scales. This research approach provides a framework to study the vulnerability and sustainability of the coupled system in different regions of the world.

GLP will build on the research of more than a decade within IGBP and IHDP core projects, especially GCTE and LUCC, along with other projects sponsored by the international global change programmes. This legacy provides the opportunity to study the coupled human-environment system in ways not possible in the past. GLP seeks to merge these existing research communities, and to attract other researchers from the social and natural sciences and the humanities.

Research Framework

GLP has three objectives that determine the research framework:

(i) to identify the agents, structures and nature of change in coupled human-environment systems on land, and to quantify their effects on the coupled system;

(ii) to assess how the provision of ecosystem services is affected by the changes in (i) above; and

(iii) to identify the character and dynamics of vulnerable and sustainable coupled human-environment systems to interacting perturbations, including climate change.

Three thematic areas emerge from these objectives: (i) the dynamics of land system change; (ii) the consequences of land system change; and (iii) integrating analysis and modelling for land sustainability. Focal areas are factors affecting decision making, the implementation of land use management, the effects on ecosystem and environmental dynamics, the provisioning of ecosystem services, and the evaluation of the land system's vulnerability to global environmental changes, or sustainability in spite of these changes.

Theme 1: Dynamics of Land Systems

Issue 1.1: How do globalisation and population change affect regional and local land use decisions and practices?

Issue 1.2: How do changes in land management decisions and practices affect biogeochemistry, biodiversity, biophysical properties and disturbance regimes of terrestrial and freshwater ecosystems?

Issue 1.3: How do the atmospheric, biogeochemical and biophysical dimensions of global change affect ecosystem structure and function?

Theme 2: Consequences of Land System Change

Issue 2.1: What are the critical feedbacks to the coupled Earth System from ecosystem changes?

Issue 2.2: How do changes in ecosystem structure and functioning affect the delivery of ecosystem services?

Issue 2.3: How are ecosystem services linked to human well-being?

Issue 2.4: How do people respond at various scales and in different contexts to changes in ecosystem service provision?

Theme 3: Integrating Analysis and Modelling for Land Sustainability

Issue 3.1: What are the critical pathways of change in land systems?

Issue 3.2: How do the vulnerability and resilience of land systems to hazards and disturbances vary in response to changes in human-environment interactions?

Issue 3.3: Which institutions enhance decision making and governance for the sustainability of land systems?

Implementation Considerations

Development of a detailed and prioritised Implementation Strategy will be an early responsibility of the GLP Scientific Steering Committee, however, it is expected that GLP will be implemented through the synthesis of prior work as well as the collection and analysis of new data. Integration across disciplines and across scales will require the development of new analytical tools, and comparisons of land dynamics across regions will require major efforts in data compilation and dissemination.

Integrated regional studies will be used to integrate biophysical and social dimensions, while smaller-scale research efforts (process or case studies and manipulative experiments) will be needed to explore the linkages between ecosystem properties and services, and between ecosystem service delivery and societal structures.

GLP will design a strategy for developing and experimenting with a wide range of models to integrate societal and natural dynamics, and will engage in IGBP and IHDP activities aimed at the epistemological, conceptual and methodological integration in the modelling of coupled socio-environmental systems.

GLP will require better access to existing data, better knowledge of data quality and generation of new data in ways which enable data sharing among researchers. GLP will develop meta-data standards for land applications, move to adopt standard land cover classification systems, develop common terminology and techniques for land cover classification, expand data archiving efforts and link with existing data management systems.

Delivery systems (websites, reports and workshops) that accelerate transfer of knowledge to all levels of society will be used, and efforts made to improve communication among researchers and between researchers and stakeholders. Existing research networks and linkages with existing mechanisms to transfer scientific results to the policy makers and decision makers (e.g. IPCC and MEA) will be strengthened. GLP will also promote north-south equity, funding opportunities and capacity building.

Introduction

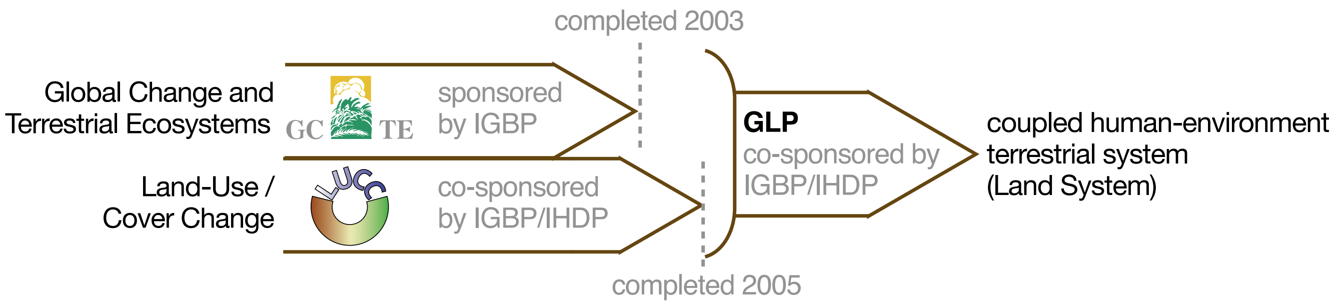
A profound transformation of the Earth's environment is currently underway – a transformation that is primarily due to the numbers and activities of people. During the last 50 years, the human population has risen from two and a half to over six billion, economic activity has increased ten-fold, and the connectivity of the human enterprise has risen dramatically through globalisation of economies and flows of people, information, products and diseases. Human transformations of ecosystems and landscapes are the largest source of change in the natural systems on Earth, affecting the ability of the biosphere to sustain life (Steffen et al., 2004; Vitousek et al., 1997). Intensification and diversification of land use and advances in technology have led to rapid changes in biogeochemical cycles, hydrologic processes and landscape dynamics (Melillo et al., 2003).

The imprint of these activities on the Earth is clear: atmospheric composition is significantly different from that of a century ago; half of the Earth's land surface has been converted to direct human use, and most of the rest is managed for human purposes; most of the world's fisheries are fully or over-exploited; and the sixth great extinction event on Earth is occurring, primarily due to the actions of just one species – *Homo sapiens.*

The Earth System refers to the global-scale coupled socio-environmental system; and the terrestrial component of the Earth System – the "land system" – stands at the centre of understanding the relationship between humans and their environment. Humans derive a wide range of goods and services from terrestrial environments, and in doing so, modify them significantly. Changes in land use and management affect the states, properties and functions of ecosystems. These, in turn, affect human well-being, decision making options for society, and the capacity of humankind to survive. At the same time, land systems are critical components of the interacting physical, chemical and biological global-scale cycles and energy fluxes that provide the conditions necessary for life on Earth, and they affect the rates of change within the Earth System.

There are two central research challenges in studying the links between human transformations of land systems and the changing role of land systems in Earth System functioning: (i) up-scaling local and regional process understanding to achieve global process understanding; and (ii) integrating the societal and environmental dimensions of the problem. Earlier work – as part of LUCC – has helped the international research community greatly increase its understanding of the natural dynamics of land use change and its consequences. It has also led to an increasing awareness of the fact that our understanding of the relevant internal societal dynamics is still very limited. At the same time, work in GCTE greatly increased our understanding of the potential impacts of global environmental change on natural and agro-ecosystems, but the biophysical perspective was largely constrained from exploring how vulnerable societies might be to that change. A major deficiency in our current understanding thus relates to the interface of the natural and the societal. GLP will build on the valuable legacy of these past research efforts to help address these challenges (Figure 1), but will adopt a more integrated approach to land systems research.

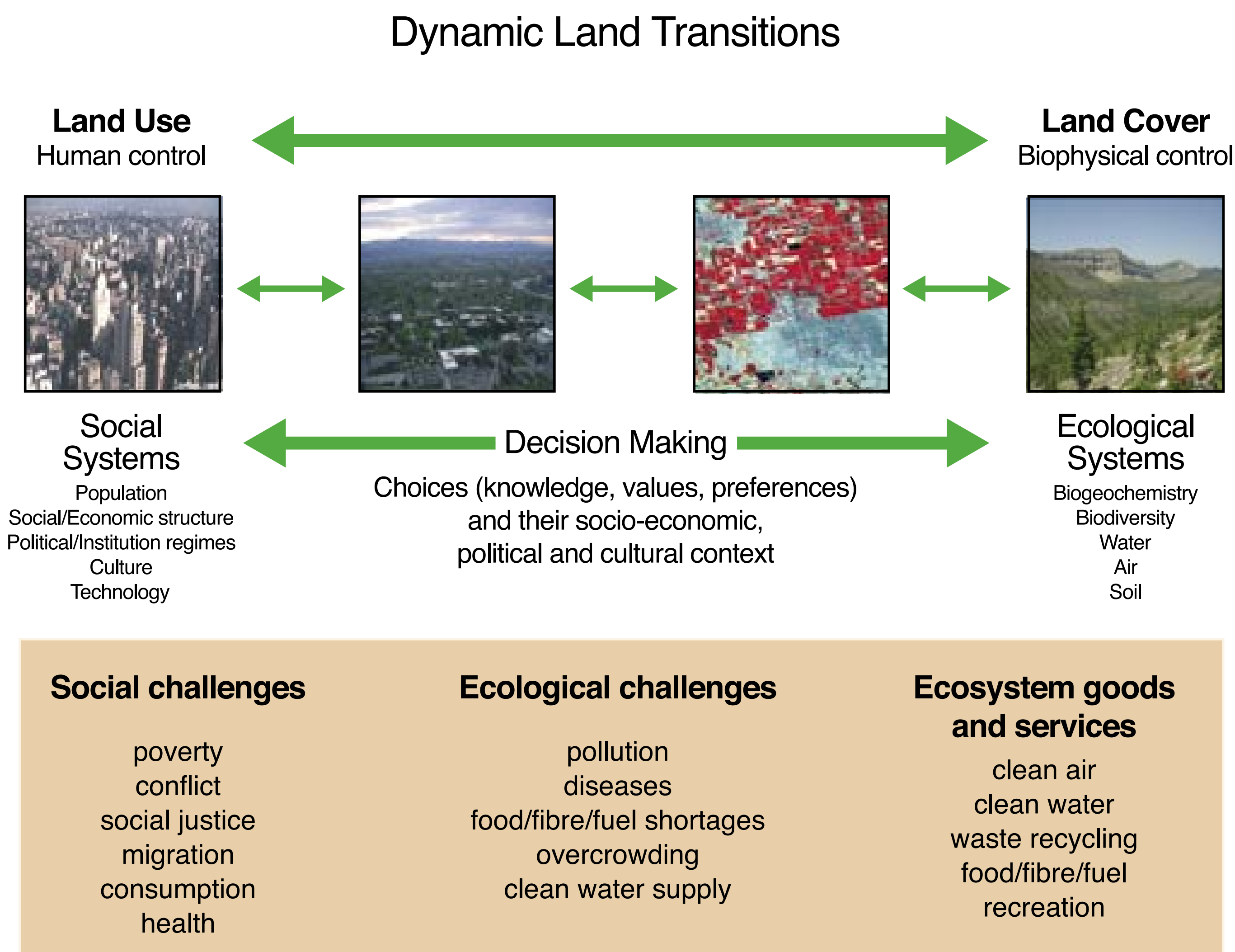
Figure 1. The genesis of GLP, emerging from previous global change projects.



There is a need for an improved understanding of how human actions affect natural processes of the terrestrial biosphere, and of the prime societal drivers and dynamics of these actions; there is an even greater need to evaluate the consequences of these changes (Kates et al., 2001; NRC, 1999) across different land systems. Every point on Earth can be defined along a continuum of states (from wilderness to mega-cities) resulting from the interactions between societal and natural dynamics (Figure 2). The dynamic of this continuum generally, but not always, moves towards increasing human occupation and impact. Abandoned farmland may return to forest, and clear-felled forests may re-grow. However, once an area carries human structures it seldom reverts to open land. The time scales of movement along this continuum vary. Human development may occur in years, even months as economic and social opportunities arise, but return to a wilderness landscape may take centuries. GLP aims to define this continuum more explicitly, to quantify the rates of landscape change, and to explain the underlying causalities and decisions involved.

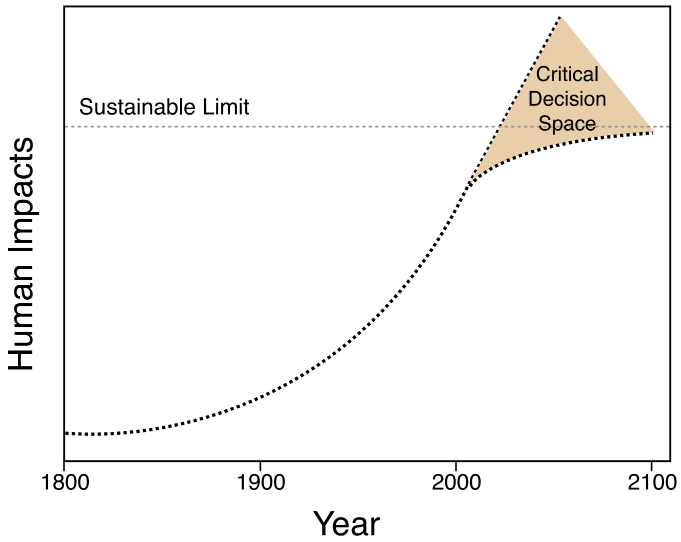
An improved understanding of how human actions affect natural processes of the terrestrial biosphere will help to assess the risks faced by societies and their environments, and the ways in which societies deal with these risks. Over the past few decades it has become apparent that growth in human well-being, if measured simplistically by gross global economic product, shows no sign of slowing. However, economic and social development is dependent on the services that the Earth provides – for example, fresh water, clean air, atmospheric temperature control, primary production, and system resilience due to genetic diversity. It is unlikely that economic growth can draw down and substitute for these services indefinitely. Rather, it is likely that there is some threshold at which the Earth System, including all its economic, technological and other societal responses, can no

Figure 2. The continuum of states resulting from the interactions between societal and natural dynamics.



longer absorb the impacts – the 'sustainable limit' (Figure 3). But what is this threshold, and when do we reach a point at which it becomes critical to transform our collective production and consumption patterns – for example through more efficient resource use? GLP will help to elucidate these issues from a land systems perspective, and thus inform considerations of effective partnerships between knowledge acquisition and governance processes.

Figure 3. Conceptual representation of the critical decision space resulting from cumulative global human impacts (population, percent domesticated land, freshwater use, biodiversity loss, and per capita gross domestic product).



The GLP goal is:

to measure, model and understand the coupled socio-environmental terrestrial system.

This coupled socio-environmental terrestrial system is henceforth referred to as the 'land system'. The GLP research goal is part of the broader efforts to understand changes in the interaction between people and their environments, and the ways these have affected, and may yet affect, the sustainability of the Earth System. These broader efforts must also deliver proposals for substantive and practicable changes in socio-environmental interaction.

Major Scientific Issues

There are major scientific issues underlying the GLP research goal that need to be addressed, including: (i) the need to move toward to a more integrative approach from the current disciplinary fragmentation of the land system science community; (ii) the need for true integration of scientific efforts to deal with the large-scale changes taking place in the land system; (iii) methods for scaling across physical and scientific dimensions of observational systems and methods, case studies, experiments, and model analyses; and (iv) methods to incorporate the historical aspects and timescales of social and environmental changes. Some of these issues are illustrated below, followed a description of the GLP research framework for addressing these issues.

Overcoming Disciplinary Fragmentation

GLP will adopt a truly trans-disciplinary approach to the study of socio-environmental systems, dealing with the necessary dynamics from a holistic and co-evolutionary perspective. In effect, this means that GLP will move from studying the dynamics as the interaction between a social system and an environmental system, to studying the dynamics as complex, simultaneous interactions between societal, natural and mixed processes at various scales. In these interactions, humans collectively define the environment, its resources, its problems and the dynamics involved. Humans try to find solutions and to implement them. Human perceptions of the environment, as well as their interactions with it (such as extraction of services), are determined by communications and social interactions occurring within society. In this sense human beings do not communicate with their environment, but among themselves about their environment (Luhmann, 1992).

In emphasising the coupling of these social interactions with biophysical processes, GLP will focus on human decision making and actions regarding the terrestrial environment (especially Theme 1) and on ecosystem services (Theme 2). These topics are at the interface of the societal and the environmental domains that co-evolve through time to shape the land and landscapes. The magnitude and excitement of the challenge here should not be underestimated, as it implies nothing less than developing the perspective, epistemology, theory and methodology of a new kind of science – and one that is fundamentally different from the disciplines currently dealing with the separate social and environmental systems.

Issues of Scale

Environmental and social dynamics operate across multiple scales, with many connections between the dynamics at different scales. This becomes all the more critical when supra-regional and global dynamics are considered. Relatively simple approaches to understanding local phenomena in the context of their immediate regions are no longer sufficient. It is crucial to distinguish and prioritise the multiple spatial scales of various interactions. The choice of scale for observation and analysis is driven by the phenomena being investigated. Hence, scale specification can limit study to an inadequate (and unconsciously biased) sample of what should be studied. Remote sensing and geographic information systems now allow simultaneous investigations at many scales, and with respect to many variables. These help in modelling different perspectives on human activities, and thus help to elaborate models of spatial decision making. However, these are only tools, the rapid development of which is not yet matched by the theory needed to determine which scales and interactions are most important.

LUCC case studies showed that not all causes of land change and all levels of organisation are equally important (e.g. Geist and Lambin, 2004). A limited number of causes seem to be essential to predict the general trend in a given land system. The syndrome approach, for example, describes archetypical, dynamic, co-evolutionary patterns of human-environment interactions, seeking to generalise recurrent interactions between driving forces which will result in certain patterns of change (Petschel-Held et al., 1999). The continued development of such predictive power at appropriate scales is a motivating challenge for GLP (Theme 3), which must also explore and develop approaches that help identify important interactions across scales, such as allometric scaling of spatial phenomena, and emergent thresholds that cause rapid changes in apparently stable systems.

Case Study Comparisons

GLP will undertake a global comparison of regional land system case studies. Global environmental changes affect the coupled socio-environmental system differently in different regions of the world. Biophysical alterations (such as increased atmospheric carbon dioxide concentrations or increased soil erosion) and social forces (such as the globalisation of markets and the media) generate different responses in the Northern Hemisphere than in the Southern Hemisphere, in urban environments than in rural environments, and in developed countries than in developing countries. These responses, in turn, shape the land by influencing local land use decisions and the provision of ecosystem services. But the converse is also true: differences in social dynamics, economic circumstances and cultural values mean that many landscapes have evolved according to unique trajectories even under similar natural conditions (Kasperson et al., 1995). Such complex human-environment systems are not amenable to simplistic replication, and their complexity means that predictability will never emerge from individual case studies. Only well constructed regional comparisons, chosen carefully on the basis of well-considered conceptual models, will provide the analytical power necessary to reach integrated and global conclusions (Theme 3). Most importantly, such comparisons are essential to distil the more salient dynamics operating on land systems at different spatial and temporal scales of analysis.

The legacy of past work in GCTE, LUCC and elsewhere, includes the demonstrated power of a range of global networks on various aspects of the biophysical environment. GLP will build on these and create new networks aimed at comparative studies of the coupled socio-environmental system at local to regional scales, to synthesise an Earth System approach that draws conclusions from regions with different characteristics and hence guides multi-scale dynamic Earth System modelling.

Using the Past to Inform the Future

It is often difficult to use even the limited knowledge of the past for improving the policy-relevance of studies of contemporary systems. This is partly because there are relatively few methods for learning from the past, and most of them depend on assuming that there will be no change in the underlying processes. If models are based on static assumptions about cause and effect, projections will be based on the risky assertion that explaining the present from our knowledge of the past is the same as projecting the future based on our knowledge of the present. In fact, many system dynamics that were not active or interacting previously now are, resulting in major changes in these second order dynamics – the ways in which the process of change itself is changing.

Studies of environmental dynamics that contribute to important policy decisions generally rely on direct historical observations of biophysical conditions that usually encompass a few decades, or at most one or two centuries (cf. IPCC, 2000; Houghton et al., 1996). However, historical data sets are often inadequate to fully describe cause and effect relationships within land systems, especially with respect to system thresholds that separate different stable system states. The availability of various palaeo-records provides the opportunity to investigate how choices made in the past have influenced present-day landscapes, and thus help to introduce a longer time perspective into policy-relevant land system projections. Carefully tested dynamic models are one way of extrapolating to future conditions, however, other approaches are also needed to inform policy (Theme 3). Methods such as scenario development (e.g. Sarewitz et al., 2000) are crucial, with logic fundamentally directed towards the future, and formulated in terms of alternatives, perceptions, choices, risks and permanent unpredictability.

Synthesising Insights in Dynamic Models

Coming to grips with such complex and relatively unknown dynamic systems will require a major integrated modelling development effort, at differing levels of abstraction and at multiple spatial and temporal scales. It will be necessary to model combinations of 'bottom-up' and 'top-down' processes, particularly to deal with emergent complex system phenomena, as these systems are intractable to other approaches. GLP will need to engage with the rapidly developing fields of complex systems and agent-based modelling, which enable study of the interactions between general processes and individually different entities, while considering spatial interactions. A benefit of this approach is forcing people from different backgrounds to focus on the same relational and behavioural issues, which may otherwise be confounded by disciplinary terminology and concepts.

Integrated modelling – the modelling of interactions between natural and societal dynamics – is a poorly developed area, generally not mature enough for predictive empirical models or decision support systems. Model development is currently aimed at models of dynamical theories concerning the interactions between human and environmental components, that are subsequently 'tested' against data to refine ideas about the functioning of the complex processes involved. As such, they are an essential step toward models that are sufficiently detailed and realistic to relate past observations to predictions of the future that are useful for land use and land cover change policy development.

Research Framework

The above issues are significant and exciting, and are important in view of current concerns about the environment. GLP will help address these issues by building on the last decade of research within IGBP and IHDP core projects, in particular GCTE and LUCC. This legacy provides the opportunity to study the coupled human-environment system in ways not possible in the past. GLP seeks to merge these existing research communities, and to attract other researchers from the social and natural sciences and the humanities.

In the face of this range of issues, GLP will focus firstly, on a clear set of questions addressing the interface between people, biota and natural resources of terrestrial systems, and secondly, on combining detailed regional studies with a global, comparative perspective.

GLP has three objectives that determine the research framework:

(i) to identify the agents, structures and nature of change in coupled socio-environmental systems on land and quantify their effects on the coupled system;

(ii) to assess how the provision of ecosystem services is affected by the changes in (i) above; and

(iii) to identify the character and dynamics of vulnerable and sustainable coupled socio-environmental land systems to interacting perturbations, including climate change.

Three thematic areas emerge from these objectives: (i) the dynamics of land systems; (ii) the consequences of land system change; and (iii) integrating analysis and modelling for land sustainability.

Focal areas are factors affecting decision making, the implementation of land use management, the effects on ecosystem and environmental dynamics, the provisioning of ecosystem services, and the evaluation of the land system's vulnerability to global environmental changes, or sustainability in spite of these changes.

Theme 1: Dynamics of Land Systems

Issue 1.1: How do globalisation and population change affect regional and local land use decisions and practices?

Issue 1.2: How do changes in land management decisions and practices affect biogeochemistry, biodiversity, biophysical properties and disturbance regimes of terrestrial and freshwater ecosystems?

Issue 1.3: How do the atmospheric, biogeochemical and biophysical dimensions of global change affect ecosystem structure and function?

Theme 2: Consequences of Land System Change

Issue 2.1: What are the critical feedbacks to the coupled Earth System from ecosystem changes?

Issue 2.2: How do changes in ecosystem structure and functioning affect the delivery of ecosystem services?

Issue 2.3: How are ecosystem services linked to human well-being?

Issue 2.4: How do people respond at various scales and in different contexts to changes in ecosystem service provision?

Theme 3: Integrating Analysis and Modelling For Land Sustainability

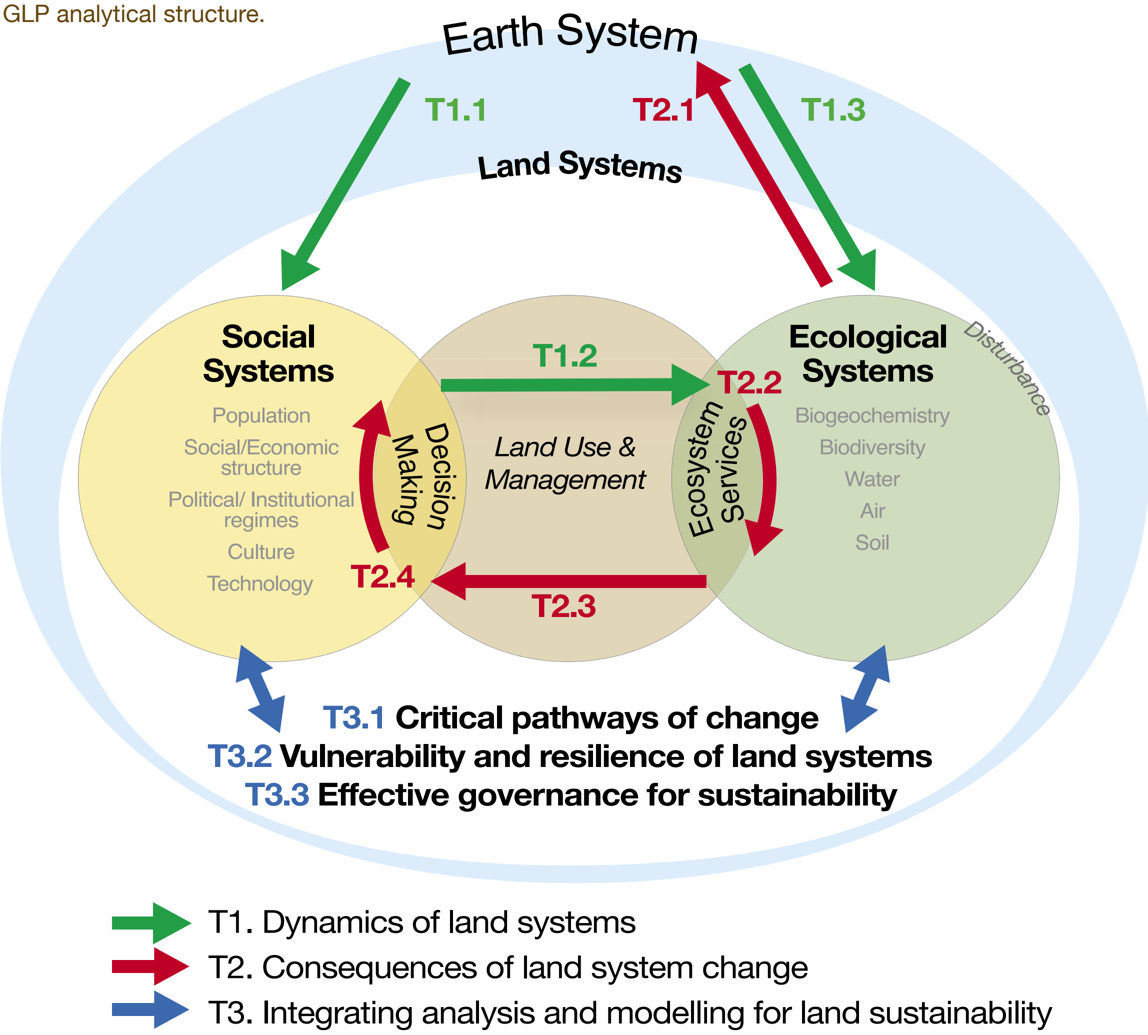
Issue 3.1: What are the critical pathways of change in land systems?

Issue 3.2: How do the vulnerability and resilience of land systems to hazards and disturbances vary in response to changes in human-environment interactions?

Issue 3.3: Which institutions enhance decision making and governance for the sustainability of land systems?

GLP success will depend on the extent to which the project contributes to the broader effort to develop an improved and more balanced strategy to deal with the environment in a sustainable manner. To contribute substantively in this regard, the research undertaken in GLP must be policy-relevant. This does not mean solely undertaking applied research, nor only research dictated by politics; but it does mean that a significant portion of the research should be directed towards responding to the issues facing society (Clark et al., 2004). This implies a shift of emphasis from question-driven research to solution-driven policy support and testing. Research is still required to answer questions, but the choice of questions to answer is strategic, giving priority to questions that need to be answered to make scientific results policy-relevant.

Figure 4: GLP analytical structure.

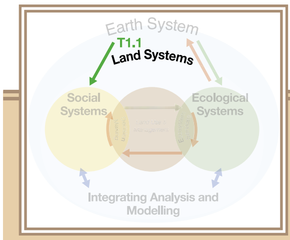


Theme 1: Dynamics of Land Systems

An understanding of global change is dependent on an understanding of the role of human activities in altering the structure and functioning of terrestrial ecosystems, and the effect of changes in the Earth System on coupled human-environment systems operating at smaller scales. Improved understanding of the decision making processes related to land use management provides the foundation for evaluating the interactions between factors influencing human activities and feedbacks within the coupled human-environment system. The impacts of land use decision making on land use and consequent cover changes and ecosystem dynamics are particularly dramatic.

This theme contributes to understanding how human activities and global environmental changes affect terrestrial and freshwater ecosystems. The theme will develop and synthesise knowledge on the proximate and underlying causes of land use change (and hence ecosystems), with particular attention to the role of broader demographic, economic, social and political forces, in shaping land use decisions (Issue 1.1). The effects of land use practices (e.g. agricultural, silvicultural and pastoral systems) on ecosystem services and the resulting feedbacks to the Earth System have not been well studied or quantified. Particular attention will be given to the effects of the human domination of landscapes, as they relate to urban areas, habitat management, the increasing impact of invasive species, and other environmental characteristics (Issue 1.2).

This theme will also seek a deeper understanding of the functioning of ecosystems within the context of global environmental change, assessing the effects of changes in atmospheric composition and physics on hydrological and biogeochemical cycles, biodiversity and ecological disturbance regimes (Issue 1.3). The greatest challenge is the integration of this knowledge to forge an understanding of the combined and interactive effects of land use and broader global environmental change on ecosystem structure and function.



Issue 1.1: How Do Globalisation and Population Change Affect Regional and Local Land Use Decisions and Practices?

Environmental changes are intimately linked to processes of globalisation. Globalisation is the growing and accelerated interconnectedness of the world in an economic, political, social and cultural sense. Due to ever less impeded flows of goods, capital, information and people, the world is becoming interconnected, with distant peoples sharing knowledge and lifestyles, and different institutions functioning as parts of one complex system. As a consequence, local situations and events are increasingly perceived as being influenced by unpredictable external factors (Göbel, in press). Globalisation increasingly separates places of consumption from places of production, such that land systems often cannot be adequately understood without knowing their linkages to decisions and structures made elsewhere (Blaikie and Brookfield, 1987). For example, commodity crops throughout Africa are directly contracted from Europe (Bassett, 2001), and large-scale deforestation in Borneo is driven by Japanese timber and pulp wood industries (Brookfield et al., 1995). The translation of the demand to land systems is however, typically mediated by local policies and institutions (Angelsen and Kaimowitz, 1999). In either case, the dynamics in question are embedded within, and often directly tied to, decisions made halfway around the world, or to processes operating globally. Research is needed on the ways in which the socio-economic forces of globalisation are tied to specific suites of land use practices, and the role of institutions in mediating their outcome – including their impacts on ecosystem services, and especially under rapid and large-scale change.

Analysis of the political economy, institutions and stakeholders in land use decision making in regions undergoing socio-economic and environmental change is critical for various kinds of land change models, and provides insight into what types of appropriate coping strategies might be taken at the local and regional scale. Special attention should be given to those socio-economic and political changes resulting in the relocation of significant numbers of people, both between regions and within regions. Understanding these interactions and how they affect ecosystem services – which are in many cases altered by changing land use practices – will facilitate the development of coping and mitigation strategies to offset further perturbations.

Globalisation and Land Change

Contemporary globalisation intensifies global interconnectedness in all aspects of social life (Held et al., 1999). A phenomenon may be considered to encompass globalisation if it represents the removal of a barrier to interconnectedness, or an increase in the degree of interconnectedness between places. One key principle of globalisation is that "developments in one part of the world have important consequences for the life chances of individuals and areas in other parts of the globe" (Gibbs, 2000). The specific outcomes of globalisation vary spatially, and include the development of international monetary and development policies, international environmental agreements, trade agreements, commodity chains, technology transfer, and the growth of transportation and communication infrastructure. The effects of globalisation on land use and more general decision making may be direct, as in the following cases.

International monetary and development policies (e.g. structural adjustment) often impose environmental conditions on nations receiving aid. These conditions may lead to altered resource use, but they may also lead to industrial developments in major cities, which may in turn, lead to a restructuring of rural-urban population dynamics and rural resource use. The consequences of globalisation on local land use are indirect in this last case. International environmental agreements (e.g. Convention on Biodiversity, United Nations Convention to Combat Desertification, United Nations Framework Convention on Climate Change, Ramsar Convention on Wetlands) establish cross-border standards for water use, carbon emissions, air pollution and resource extraction (e.g. fisheries). For example, trade agreements (e.g. North American Free Trade Act, European Union (EU), World Trade Organisation) are frequently accompanied by an assessment of potential environmental impacts, and therefore develop environmental agreements as a component of the trade agreement. Additionally, trade agreements may alter national competitiveness for natural resources (e.g. agricultural production), and consequently, result in a change in resource extraction. Teleconnections are increasingly pervasive; for example, EU regulations of feed imports altered feed production in EU communities, and altered the production of manioc chips in rural areas of northern Thailand (UK Parliament, 2002; Tanticharoen, 2000).

Global businesses (i.e. trans-national corporations) operate semi-independently of international trade agreements. For many of these businesses, geographic location may be less important than the cost of labour in their commodity chain. Therefore, the geographic location of global businesses often changes to reduce production and distribution costs (e.g. labour costs), which may have repercussions on the local socio-economic structure that influences land use options and decision making. Another aspect of global enterprises are monopoles and oligopoles. For example, seeds of major crops are increasingly controlled by a few seed companies, narrowing farmers' seed choice. The effects of this, whether positive or negative, may substantially alter the agricultural landscape in many regions of the world. The diversity of crops and livestock is increasingly reduced, endangering the sustainability of agricultural production and thus agricultural communities.

Technology transfer (e.g. genetically modified agricultural organisms, livestock, energy and water) is a means by which innovations diffuse from one region to another. Innovations diffuse when they prove successful in one region and other regions wish to adopt them. The introduction of innovations, however, may lead to different land use practices. For example, genetically modified seeds may increase agricultural output, while simultaneously requiring different inputs and investments, such as irrigation and fertiliser and pesticide use.

Market integration may have a range of land use consequences, especially on agricultural production systems, including expansion of cultivated areas, changes from subsistence to cash crops, intensification of production (including increased use of inputs) and, in the case of intensification, abandonment of agriculture in marginal lands. Increased market integration will often lead to changes in social structures, including greater (or in rare cases smaller) inequalities.

The growth of transportation and communications infrastructure and financial interconnectedness facilitates the transfer of knowledge and technology around the globe. This transfer may indirectly facilitate other forms of land use change, such as migration and changes in lifestyles and value systems. Additionally, the building of transportation networks can directly alter ecosystems (e.g. road-building in tropical forests).

These effects of globalisation on local land use change have been examined under LUCC, as well as under Global Environmental Change and Human Security (GECHS), Land-Ocean Interactions in the Coastal Zone (LOICZ), Institutional Dimensions of Global Environmental Change (IDGEC), Industrial Transformation (IT) and Urbanisation, and the cross-cutting projects of the ESSP – the Global Carbon Project (GCP), Global Environmental Change and Food Systems (GECAFS) and the Global Water System Project (GWSP). However, only a partial understanding of the interactions between globalisation and local land use has been gained to date.

Detailed case studies would help to explain both the forces driving market integration (exogenous factors imposed on subsistence-oriented farmers through national policies and development projects, and endogenous response to other external factors, such as infrastructure development and changing preferences with respect to consumption and lifestyles), and the land use consequences of market integration. A more general understanding would be gained through comparative case studies of the processes by which drivers of change from multiple scales interact (conceptually and from a modelling standpoint), including the role of cities as focal points of globalisation that cause rural-urban restructuring. Global synthesis is needed to understand and explain the spatial patterns of globalisation and their land use consequences in distant places.

Population Dynamics and Land Use Change

Demographic factors, including population growth, density, fertility, mortality, age and sex composition of households, are known to be important factors influencing land use and land cover change. Research over the past decade has shown that while population growth is strongly related to land cover dynamics such as deforestation (Allen and Barnes, 1985), this relationship is mediated by many other factors, such as land settlement policies and market forces (Geist and Lambin, 2002). A key aspect of demographic dynamics is human migration, including shifts to and from rural and urban areas, a migration commonly linked to globalisation. While urban areas continue to draw labour from rural agricultural areas, global labour markets induce the movement of large numbers of people across countries and continents. Meanwhile, large-scale planned re-settlement continues in Amazonia and Indonesia, where land use patterns have been found to depend on household composition, income, soil fertility, distance to markets and the duration of tenancy (NRC, 2005). Land tenure itself can affect household-level decisions that determine

Box 1. Globalisation

Globalisation refers to the networks of interdependence across countries created largely by the flow of goods, information and ideas. Globalisation has its roots in the mercantilism of the 16th century, and has steadily increased over time. Confronted with the dynamics of global markets and flows of energy, matter and information across boundaries, national and international governments, governance structures face new challenges in their attempt to control, regulate or play a key role in a global economy.

Figure 5. Transport of timber from tropical forests. © Digital Vision Ltd.

The environmental impacts of globalisation, and further liberalisation of international trade are top items on policy agendas. Since 1970 more than 700 multilateral environmental agreements have been created. Many of these aim not only at the remediation of environmental problems, but seek solutions for sustainable use of ecosystems. Kates (2003) argues that globalisation will lead to further declines in population growth, but will increase consumption levels, trade and transport, and spread models of resource use based on Western development approaches.

The IHDP IT project is based on the assumption that important changes in production and consumption systems will be required in order to meet the needs and aspirations of a growing world population, without continuous deterioration of the world's ecosystems. It aims at better understanding the transformations of coupled systems, taking into account the role of technological change and institutions for the effective governance of transition processes.

fertility, with more secure tenure resulting in lower fertility (Moran, 1993). Establishing the generality of such findings is an important research challenge.

Understanding of these relationships will improve largely through detailed case studies of major cases of migration, the underlying causes of such migration, and the consequences for the areas that have lost and gained population. Consequences may include the use of remittances and the transfer of knowledge or technology, and equity outcomes of land concentration, land scarcity, land degradation and agricultural indebtedness. As a complementary set of activities, national-scale assessment of the magnitude of rural depopulation across the Earth in the 20th century and the implications for land cover, land use and human well-being would also improve the understanding of the interactions between population and land use change. In this case also, detailed case studies should be followed by comparative studies of migration processes, with attention to the broad-scale changes in biogeochemical cycles and ecosystems affected. In these activities, the prospects for the 'demographic transition' should be evaluated, as well as the likelihood that developing countries will follow the pattern of industrialised countries, with increased rural depopulation and urban concentration.

Political and Economic Transitions, Policy Failures and Land use

Political and economic transitions have powerful impacts on what happens to land. Land use is affected by policies, and these policies can shift gradually or suddenly. Indeed, the only large-scale ecosystem collapse of modern times – the case of the Aral Sea – is intimately tied to a chain of decisions emanating from the former Soviet State, translated into large, inefficient irrigation systems on the two rivers feeding the sea (Micklin, 1988). Important processes include the transition from command economies of the Eastern Block and the Soviet Union to market economies; the decentralisation of governance being promoted by some nations and at times by international lending agencies and non-governmental organisations (NGO); and transitions, such as those being proposed to move societies towards sustainability. At times of transition, a number of things take place. Past structures are reassessed for their utility and new networks and patterns emerge. Population shifts may take place as the economy shifts in orientation. There can be considerable disorganisation as old patterns try to persist, new ones emerge, and considerable inefficiencies make their way through this transitioning system. At these times there may be considerable neglect of environmental conservation and potential pollution, because regulatory agencies may not be operational or effective. These societies in political and economic transition offer many opportunities to examine the dynamics of the relationship between the political-economic sector and land use, land cover and human well-being.

All parts of the world have been subjected to social shocks, and subsequent movement of human populations, as well as pandemics. While the effects of these shocks are generally localised, their impact usually trumps all other factors in shaping regional land use. Armed conflict, including both full-scale international wars and small-scale civil unrest, may have profound effects on society and land use. Effects may be of short or long duration, and may be associated with the creation of uncertainty (e.g. access to land and other resources), with forced or voluntary depopulation of insecure areas, with disruption of supplies of inputs and marketing of outputs of productive activities, as well as with the direct impacts of conflicts (e.g. the use of chemical agents and land mines).

Detailed case studies will reveal the conditions under which communities self-organise to manage their resources and their affairs following the breakdown of political and economic systems, and the policies that impede self-organisation. Systematic comparative research will determine under what conditions decentralisation provides better land management (as measured by reduced deforestation and land degradation) than more centralised approaches. Cross-national studies will be conducted to assess the relative speed of these transitions, their environmental costs and consequences for population location, human health and welfare, the feedbacks that lead to the eventual correction of these transitional costs, and the relationship between drug trafficking, money laundering and land cover change.

Local Knowledge, Values and Land Use

The scientific community has a large number of disciplinary approaches and methodological instruments to study and partly quantify the effects of global change. While many of these results are communicated to the public, it is unclear if, or how, socio-economic or environmental changes are perceived in different communities around the world. For example, local communities surrounding biosphere reserves may hold very different views about what constitutes a 'healthy' or 'best case' forest from those held by biologists or preserve officials (Haenn, 2003). Understanding these perceptions is an essential prerequisite for understanding the magnitude of potential reactions. Undoubtedly, the perception of global change can only be analysed in the context of the knowledge and value systems of local societies. Furthermore, there is a need to investigate the link between communication channels (e.g. mass media, internet) and the homogenisation of lifestyles and consumer preferences like consumer goods, which might act indirectly, but in the case of diets, act very directly, on land use change.

Additionally, studies on local attitudes towards the environment are crucial for education and community conservation-based programmes. School development in rural and urban contexts needs attention. Research should focus on the traditional systems of learning, including teaching and learning processes. It is crucial to work closely with teachers, parents and children in order to understand how they learn, and to assimilate and transform the information given for the promotion of environmental values and attitudes towards nature. This will help establish concrete and methodological proposals in the areas of conservation education and science teaching. The role of the media in transmitting environmental information is immense, and there is a need to analyse how communication and information are influencing people's knowledge about their environment.

Detailed case studies will highlight the ways in which knowledge and value systems (especially "traditional"/ indigenous knowledge) and lifestyles are related to land use options, and how they are mediated by education and mass media. Comparative analysis will reveal paradigmatic decision making processes and their temporal and spatial impact.

Box 2. Illicit Land Use Practices

Illicit land use practices throughout the developed and developing world have a significant impact on land cover change. Coca, marijuana and opium poppy production has resulted in significant deforestation in regions such as the highlands of Burma and Thailand and Andean countries. Research at the Sierra Madre de Santa Marta of Colombia found significant deforestation owing to coca production. Drug production areas are often conflict-ridden and lawless, leading to ecologically detrimental land use practices. Drug profits, in turn, can be laundered through tourist resort developments, as has happened in highly sensitive coastal ecosystems in Mexico's Yucatán. Illegal logging in protected areas has been tracked by Global Forest Watch using remote sensing imagery and detailed land tenure records. Researching illicit land use practices is politically sensitive and fraught with risk, yet illicit land uses cover significant areas in many parts of the world.

Figure 6. Illicit tree-felling in a tropical forest.
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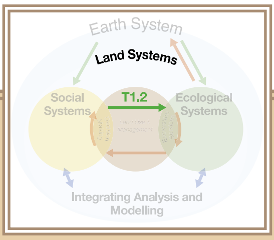
Summary

- Analyses the political economy, institutions and actors in land use decision making in regions undergoing socio-economic and environmental change.
- Studies the forces driving market integration and their land use consequences, especially on agricultural production systems.
- Calls for comparative case studies to understand the interactions of drivers of change on multiple scales and for a global synthesis to understand the spatial patterns of globalisation and the land use consequences.
- Encourages a research strategy with detailed case studies, comparative analyses and national-scale assessments to understand the interactions between population dynamics and land change.
- Examines the dynamics of the relationship between the political-economic sector and land use, land cover and human well-being.
- Analyses detailed case studies and undertakes systematic comparative research of the consequences of political and economic transitions and land use policy failures.
- Develops a research programme on the perception of environmental changes, environmental values and attitudes towards the environment to advance understanding of different systems of knowledge and various learning processes in the context of land system changes.

Contributing Community

LUCC (Focus 1), IDGEC, IT, Urbanisation, GECHS, LOICZ, DIVERSITAS, GECAFS networks of agricultural economists for major food production systems, Population-Environment Research Network, Centre for Indigenous Knowledge for Agriculture and Rural Development, Northern Eurasian Ecosystem Science Project Initiative (NEESPI), hazards community, and human and cultural ecologists and demographers.



Issue 1.2: How Do Changes in Land Management Decisions and Practices Affect Biogeochemistry, Biodiversity, Biophysical Properties and Disturbance Regimes of Terrestrial and Freshwater Ecosystems?

Increased understanding of the decision making processes related to land use management provides the foundation for evaluating the interactions between factors influencing human activities and their impacts on ecosystem structure and function. In this context, the decision making processes affecting land management are of particular interest in understanding how the range of settlement patterns, extraction and production practices, land conversion methods and conservation practices affect ecosystem dynamics. Thus, the goal of Issue 1.2 is to evaluate the impacts that changing land management practices have on key ecosystem properties related to biogeochemistry, biodiversity and biophysics.

Human transformations of the landscape are already the largest source of change in the biosphere, and this impact is growing (Vitousek et al., 1997). Land management regimes combine intentional environmental modifications (e.g. fertilisation, irrigation) as well as certain types of disturbance associated with the use of the land (e.g. grazing, deliberate use of – or protection from – fire). Reciprocal adaptation may be reached between human and ecological systems when land management regimes persist over long periods of time, and under conditions of gradual change. New ecosystems may arise through unique combinations of organisms under modified environmental conditions. These 'emergent ecosystems' may lead to novel modifications of ecosystem structure and function. However, management regimes can change abruptly as a result of environmental and/or human shocks, perturbing this 'equilibrium'. For example, expansion of agricultural lands due to market or local demands for food production, sudden changes in prices of agricultural inputs (e.g. oil prices), policy shifts which alter the environmental valuation of certain ecosystem properties, or political crises, can result in rapid transitions in land management regimes. These examples indicate the need to analyse the ways in which environmental subsystems are affected in terms of changes in biogeochemical cycles, biodiversity characteristics and biophysical properties along an urban-wildland continuum.

Impacts of Land Use Intensity and Changes in Land Use Activity on Ecosystem Dynamics

Human activities directly or indirectly affect terrestrial and freshwater ecosystems worldwide. The intensity of land management modifies the rates of biogeochemical processes and exchange, biodiversity, and flows of energy and water. For example, the manner in which pastoral systems develop in Eurasia, or in which agricultural expansion takes place in Africa or other tropical regions, is uncertain relative to the roles of industrial sources of fertilisers, the development of irrigated lands, and the use of mechanised equipment in land use practice modifications. Currently, a comprehensive information base on the different land management practices used in different parts of the world does not exist, although some information has been compiled on global farming systems (Dixon et al., 2001), irrigation systems (Doll and Siebert, 2002), croplands (Ramankutty and Foley, 1998) and livestock (Kruska et al., 2002). A concerted effort is needed to develop a functional classification of these practices in terms of their effects as disturbance regimes (e.g. fire, grazing, cropping).

New research is then needed to characterise how ecosystems are affected by changes in these land management activities, especially as they relate to effects on the biogeochemistry, biodiversity and biophysics of agricultural, silvicultural and pastoral systems. For example, the effects of intensive versus extensive agricultural management strategies altering the dynamics of the lateral and gaseous fluxes of key biological and biogeochemical compounds. Comparative studies of land use effects on ecosystem dynamics should be conducted across gradients of land use intensities, and complemented by regional and global analyses of land use characteristics including crop rotations, livestock management, input levels and other land management information. Ecosystem changes associated with different land use conversions should also be studied in a systematic way.

Spatial Relationships of Different Land Uses and Ecosystem Properties

The spatial patterns of land use can affect regional environmental conditions such as net nutrient releases, biological interactions, disturbance patterns, atmospheric chemistry and regional weather patterns. The ecological impacts of changes in management regimes range across all scales from local to global, and can be highly non-linear. For example, they may cause switches in the nature and/or spatial pattern of land cover, result in the relocation of human populations, modify biodiversity (e.g. fragment animal and plant populations, or favour invasions or outbreaks of pests or exotic species), or alter biogeochemical process rates. The spatial connectivity between different land uses can affect ecosystem dynamics due to modifications of biological interactions, fluxes of water and nutrients, or disturbance regimes such as fire or grazing. These impacts can then lead to changes in ecosystem dynamics, which may in turn affect the human systems that depend on them.

Land management not only affects spatial patterns of land use, but also temporal interactions across landscapes. Land management practices are often applied asynchronously across adjacent landscapes, so that water and biological and nutrient resources are differentially affected. For example, fire, grazing and opportunistic cropping, can create complex changing mosaics of impacts across drylands with emergent implications at regional scales. Such temporal and spatial modifications can also lead to the emergence of new landscape and ecosystem dynamics. How these affect ecosystem structure and function is unclear, and additional issues exist including: (i) how does land use in one part of the landscape affect other (contiguous, surrounding and distant) areas?; (ii) what are the ecosystem and socio-economic responses across space and time?; (iii) how do local land use decisions manifest themselves at the regional scale?; (iv) how does land use change outside of protected areas affect ecosystem characteristics within protected areas?; and (v) how do protected areas influence the social and environmental characteristics of the surrounding areas?

These issues will be investigated through spatial analyses of the effects of landscape characteristics of different land uses on ecosystem processes such as water fluxes, seed dispersal, disturbance regimes and plant-animal relationships. Studies will be initiated of the roles that landscape patterns and land use play on ecosystem and community development, including expansion of invasive species and development of 'emergent ecosystems'. A set of studies will be developed to evaluate the effects of landscape and land use patterns on ecosystem functioning and exchanges of water, nutrients, energy and biotic resources.

Land Use Impacts on Ecosystem Structure and Function Across the Urban-Wildland Gradient

Urban expansion is occurring faster than population growth, even with the majority of projected population growth expected to occur in and around cities. Therefore, coupled urban socio-environmental systems are an increasingly important in terrestrial research. Although urban land is currently only about 2% of the land surface, urban areas impact large areas due to the magnitude of the associated energy, food, water and raw material demands. The biogeochemistry of urban areas is unique in important ways. Human activities truly dominate these ecosystems, with fertiliser applications, energy use, structural modifications, watering regimes and species assemblages often distinct in urban communities. Urban levels of many trace atmospheric gases are elevated and can affect biogeochemical interactions (Pataki et al., 2003; Chamedies et al., 1994).

Rural ecosystems have also undergone marked land use changes, with well-documented cases of woody encroachment, increases in invasive species, landscape fragmentation and soil degradation. The ways in which environmental subsystems are affected in terms of changes in biogeochemical cycles, biodiversity characteristics and biophysical properties need further study along urban-wildland gradients.

Studies should address the following questions: (i) how do urban consumption patterns, globalised economies and the spatial configuration of urban development drive global land change?; (ii) how does decision making in transition zones (e.g. urban-agricultural gradients) alter land management practices and affect biogeochemical cycles?; and (iii) how do urban areas affect ecosystem structure and functioning within their footprints?

The existing network of urban ecosystem studies will be expanded, and organised around a common set of questions and methods to address ecosystem changes along the urban-wildland gradient. Metrics will be defined for discerning changes of key ecosystem properties along this gradient, and new tools and methods will be developed for detecting the effects of human-related structural changes in land surface characteristics and ecosystem properties along this gradient.

Summary

- Explores the impact of changing land management practices on key ecosystem properties related to biogeochemical cycles, biodiversity characteristics and biophysical properties along the urban-wildland continuum.
- Expands the information base on different land management practices to characterise these activities and evaluate how ecosystems are affected by changes in land management.
- Develops a systematic set of studies of land use effects on ecosystem dynamics, including comparative studies across gradients of land use intensities complemented by regional and global analyses.

Box 3. Peri-urban Areas

Urban expansion into peri-urban areas is a common feature throughout many regions of the world. Peri-urbanisation refers to a highly dynamic process where rural areas, both close to, but also distant from, city centres become enveloped by, or transformed into, extended metropolitan regions. These changes are usually rather piecemeal and non-uniform processes, but involve a complex adjustment of social and ecological systems as they become absorbed into the sphere of the urban economy (Simon et al., 2004).

Figure 7. The urban-rural interface in Shenzhen, China. Provided by K. Seto.

Peri-urban areas are a key interface between urban and rural areas due to the provision of essential services in both directions. They suffer the negative consequences of urban areas, and have also been neglected in most urban and environmental studies. Hence, the IHDP core project on Urbanisation has identified land conversion in peri-urban areas as one of the critical areas of research, and recommends the inclusion of urban planning and policy perspectives into studies of urban land use change (Schneider et al., in press). Joint research issues related to changes in ecosystem services and land use decision making between the Urbanisation project and GLP will be studied in collaborative activities.

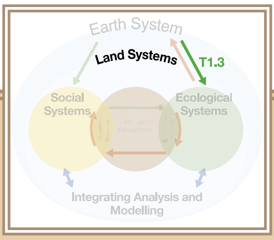
- Initiates studies related to the temporal and spatial dynamics of landscape characteristics and land use patterns, and their role in ecosystem processes, ecosystem functioning and community development.

- Analyses how urban consumption patterns, globalised economies and the spatial configuration of urban development drives land use change on different scales.

- Develops a common framework and new tools and methods to assess how decision making in the transition zones of urban areas alters land management practices and affects biogeochemical cycles and ecosystem structure and functioning within their footprints.

Contributing Community

IT, IDGEC, Analysis Integration and Modelling of the Earth System (AIMES), LUCC (Foci 1–3), DIVERSITAS, Urbanisation, Scientific Committee on Problems of the Environment (SCOPE) project on emerging ecosystems, GCTE Terrestrial Ecosystem Responses to Atmospheric and Climate Change (TERACC), GCP, GECAFS, LOICZ, Urban Long Term Ecological Research, NEESPI, the World Conservation Union, Millennium Ecosystem Assessment (MEA), Intergovernmental Panel on Climate Change (IPCC), International Union of Forest Research Organisations.



Issue 1.3: How Do the Atmospheric, Biogeochemical and Biophysical Dimensions of Global Change Affect Ecosystem Structure and Function?

Climate change and alterations in the chemical composition of the atmosphere have a direct impact on ecosystem dynamics. Global environmental change is having a direct impact on various aspects of ecosystem dynamics, ranging from biogeochemical cycling, changes in biodiversity, and the frequency and intensity of disturbance events (e.g. pest outbreaks, fire regimes and storms). The magnitude and patterns of these impacts are not well documented. Biogeochemical budgets are still incomplete, and controversy continues over the existence and magnitude of the 'Northern Hemisphere carbon sink'. Yet new insights concerning various gaseous, organic and lateral fluxes suggest approaches leading towards balancing these biogeochemical budgets (Matson et al., 2002; Melillo et al., 2003).

The loss of species and changes in species composition across various trophic levels are modifying ecosystem structure in novel ways, however, the ways in which these changes affect ecosystem function is poorly understood (Loreau et al., 2001; Wardle, 2002). Furthermore, given the changes in the global environment and the associated changes in biodiversity, it is still uncertain how ecosystems will respond to disturbances, especially when taking into account their non-linear nature and the thresholds involved. Evaluation of how biodiversity changes affect biogeochemical cycles is one way of quantifying biodiversity feedbacks to global environmental change.

Changes in climate and biotic interactions have altered the disturbance regimes resulting in modified environmental conditions that affect successional sequences. Terrestrial and freshwater ecosystems are affected by multiple perturbations at different spatial and temporal scales, for example, land use change, atmospheric carbon dioxide, nitrogen deposition, warming, biotic changes, pollutants and toxic substances in air, soils and water (Körner, 2000; Mooney and Hobbs, 2000; Sala et al., 2001; Matson et al., 2002; Rustad and Norby, 2002; Reynolds and Stafford Smith, 2002). The multi-stressor nature of global environmental change requires an understanding of the interactive (and often non-linear) nature of the stressors, of how ecosystem processes affected by the multiple stressors are modified, and of the overall effect of these stressors on ecosystem functioning. Special attention is required to identify critical non-linearities (e.g. thresholds) and feedbacks in ecosystem responses that affect resilience and the sustained capacity of ecosystems to deliver critical services.

The overarching goal of this research area is to quantify sources and sinks of nutrients, carbon and water, and to close the biogeochemical budgets in natural, managed and urban ecosystems for a wide range of specific locations, systems, and spatial and temporal scales under the influence of interacting global change drivers. In meeting these goals it will be particularly important to pay attention to the effects of variability and extremes in biophysical system drivers.

Effect of Climate and Atmospheric Composition Changes on Ecosystems

There is ample evidence that recent directional changes in climate and increased atmospheric carbon dioxide concentrations, nitrogen deposition and air quality are already affecting terrestrial and aquatic biogeochemical cycles, vegetation dynamics and distribution, species diversity, trophic structure, and the ability of ecosystems to provide food, water and other services (Körner, 2000; Matson et al., 2002; Jackson et al., 2001; Baron et al., 2002; Parmesan and Yohe, 2003; Felzer et al., in press).

It is now clear that nitrogen deposition is exceeding the retention capacity of terrestrial ecosystems in some regions, and nitrogen is leaking into adjacent aquatic systems. Furthermore, evidence is now increasing that runoff from nitrogen-saturated landscapes is producing anoxic zones in coastal oceans, for example, at the mouth of the Mississippi River. The nature, intensity and spatial extent of these cascading impacts, and particularly the rate at which they may arise, need to continue to be clarified and integrated more closely with the effects of other drivers of global change.

High latitude warming has increased growing season lengths by 2–4 weeks in the Northern Hemisphere over the last fifty years. Vegetation has responded with earlier spring phenology leading to longer drought effects in

Box 4. Land Processes in Relation to the Physical Climate

Just a decade ago, land systems were considered passive recipients of climate changes, the dynamics of which were largely driven by the ocean-atmosphere system. It is now understood that land systems are active players, not passive spectators, in climate dynamics (Steffen et al., 2004).

Land systems influence climate in several ways. Vegetation affects the physical characteristics of the land surface, which affect water evaporation and transpiration, the reflection or absorption of solar radiation, and the transfer of momentum with atmospheric flows. These processes determine water and energy exchanges with the atmosphere at its lower boundary, and can exert a major influence on climate at all scales. Land systems also affect the cycling of chemical elements, the most prominent and well-known being the carbon cycle, in particular the role of land systems in modulating atmospheric concentrations of the greenhouse gases carbon dioxide and methane. Land systems are a significant net sink for atmospheric carbon, but the longevity of this sink is a matter of intense debate and research. Land systems also influence climate through the production of the greenhouse gas nitrous oxide and through the emission of volatile organic compounds, which influence cloud physics and precipitation processes.

The spatial patterns of land systems can have surprising feedbacks to climate. Various patterns of “wet” and “dry” surfaces (e.g. vegetation and dry soil) can have dramatic effects on regional precipitation patterns. The same overall ratio of wet to dry surfaces can produce significantly different rainfall patterns, depending on the spatial arrangement of the different surfaces. Vegetation rooting patterns and soil characteristics and activity are also very important for soil moisture and soil moisture uptake by plants, which influence the partitioning of water between evaporation and runoff, and hence influence the amount of energy transferred between land and the atmosphere.

Finally, land systems can affect the climate through changes in biodiversity, because of indirect impacts on the biogeophysical and biogeochemical effects described above. For example, manipulative experiments of land system biodiversity suggest relationships between diversity and primary productivity, and diversity and nutrient cycling, both of which influence the exchange of greenhouse gases between land and the atmosphere. Biodiversity can also act as a buffer against rapid change in the structure of land systems, which could in turn could influence climate.

As land systems are likely to change significantly in both structure and function in the coming century, feedbacks from land systems to climate are becoming increasingly important in Earth System science.

the summer. Significant uncertainties exist regarding the different stressors and their interactions with ecosystem processes and different levels of biodiversity (genotype, species, functional groups). In most cases regional-level drivers and impacts are significantly different from the global averages (e.g. greenhouse gases, air quality, nitrogen deposition and climate). Research is required to attribute changes across the full set of impact mechanisms, including natural variability and direct and indirect human influences at global and regional levels.

There is a need to harmonise data on multiple environmental stressors and the resulting cascades of ecosystem impacts, from the local up to the global level. Advanced models need to be developed to evaluate ecosystem responses to multiple stressors, such as climate change, atmospheric carbon dioxide concentration increases, nitrogen-additions, ozone changes and ultra-violet radiation. These models need to improve the integration of biogeochemistry, biodiversity and disturbance dynamics.

Impact of the Seasonality and Inter-annual Variability of Extreme Climatic Events on Terrestrial Systems and Disturbance Regimes

There is abundant empirical evidence of recent directional changes in climate in different parts of the world that involve both shifts in rainfall distribution and stepwise increases or decreases in average rainfall. For example, evidence suggests that global disturbance regimes have shifted with what were once 1-in-100 year events now

Box 5. Fire and Insects

Fire and insect outbreaks have been part of the natural cycle of many forested ecosystems, and fires are an important in resetting the successional cycle of forest ecosystems. Recent studies have shown however, that the frequency of insect outbreaks has increased because increased growing season temperatures have resulted in large areas of dead or damaged trees (Logan et al., 2003). Expanded areas of insect-damaged forests have the potential to enhance fire extent and intensity under altered climate conditions. Improved understanding is required of how the elements of disturbance regimes (the rate, frequency, intensity and extent of disturbances) may be affected by global change.

Figure 8. (a) Pine forest in Eastern Oregon, two years after the catastrophic fires of 2002. Note the lack of regeneration in detrimentally burned soils. Provided by Kathy Hibbard. (b) Pine beetle damage (provided by Kathy Hibbard); with inset showing mountain pine beetle (provided by USDA Forest Service).

regularly reported, and the frequency of major wildfire seasons (burning over 3 million ha) in the western United States increasing. The frequency of extreme climatic events (e.g. drought, flooding, hurricanes, changing frequency of El-Niño Southern Oscillation (ENSO) events) and their effects on disturbance regimes (e.g. fire and pest outbreaks) are expected to increase with future climate change.

Despite the large impact that such events have on ecosystem structure and function, a spatially and temporally explicit database of extreme disturbance events does not currently exist. Adequate data on the impacts of such events on ecosystem structure and function are similarly lacking. Quantification of non-linear feedbacks and cross-scale interactions are needed, as well as identification of critical thresholds that exist between disturbance behaviour and landscape attributes, such as connectivity and heterogeneity (Peters et al., 2004).

A key requirement therefore, is the establishment of a global database of extreme events, and a research programme to quantify the impacts of these events on ecosystem structure and functioning, including the propagation and spread of disturbances in fragmented versus highly connected landscapes. Integrated research efforts to quantify the impacts of extreme events on ecosystem properties and dynamics must be promoted, including the effects on biogeochemical cycling and land-atmosphere interactions, biodiversity, air and water quality, patterns of ecosystem recovery, and impacts on the provision of essential ecosystem services to human society across spatial and temporal scales. Threshold responses and extreme event impacts must be built into the next generation of integrated dynamic ecosystem models that include improved mechanistic connections between terrestrial and freshwater systems.

Impact of Toxins and Pollutants on Ecosystems and Human Health

One major perturbation to the main biogeochemical cycles arises from the fact that human industrial activity is giving societies a vast new array of useful, but possibly dangerous, organic and inorganic chemicals and products. The larger part of existing work on biogeochemical cycling at the global scale is focused on natural cycles as affected by perturbations mediated through mainly natural processes. Yet many more exotic products, for which minimal risk assessments are made, may be having low-level toxic effects on both humans and natural ecosystems.

Four classes of such products include endocrine disrupters, pharmaceuticals, (including antibiotics), other organic compounds, and metals. The detection of such products far away from their site of use, even at the South Pole, and disposal all around the globe is cause for serious concern, and it has been suggested that their negative effects may be so pervasive as to threaten the performance of humans and other species (Kolpin et al., 2002; Porter et al., 1999). While there is a large volume of such data and research results, there has not been an assessment of the global extent of occurrence and impacts of those products. The potential effects of these chemicals on ecosystem processes, such as decomposition and rates of primary productivity, and hence effects on the main biogeochemical cycles, are unknown. GLP should promote the establishment of multiple-scale studies that explore the effects of novel organic compound mixtures on physiological, species, community and especially ecosystem-level processes, thus linking the natural and anthropogenically derived processes affecting cycling. Ecosystem modelling must begin to incorporate toxic material transport and ecosystem toxicity impacts.

Impact of Changes in Land and Water Management or Land Use on Atmospheric Composition and Climate

Population growth increases demand for natural resources, affecting all ecosystems. Overexploitation of tropical and temperate forests and tropical and subtropical grasslands, and ever-expanding agriculture in all climate zones have led to land cover change, severe land degradation, soil erosion and increased runoff. There is ample evidence of the impacts that land management changes (e.g. agriculture, grassland and forest management) (Vitousek et al., 1997) and water management (Gleick, 2003) have on biophysical characteristics and biogeochemical cycling. Changes in biophysical characteristics and biogeochemical cycling alter the energy budget, atmospheric composition, radiative forcing, evapo-transpiration and precipitation regimes, and ultimately alter the sources, sinks and cycling of water, carbon and nutrients, which all affect ecosystem processes and their continued provision of services.

While large data sets exist on atmospheric carbon dioxide concentration increases due to land use change, only limited information is available on the effects of land use change (deforestation in tropical zones, overgrazing and rain-fed agriculture in arid zones) on aerosol production (carbonaceous aerosols from fires, mineral dust from

Box 6. ARIDnet

Land degradation in drylands (i.e. desertification) is of major societal concern because of the impacts on human populations (e.g. food security, economics and sustainability) and environment quality (e.g. dust storms, trace gas emissions and soil erosion). A joint GCTE and LUCC initiative on this global problem has been coordinated by the Assessment, Research and Integration of Desertification research network (ARIDnet). ARIDnet is organised around three nodes (North-South America, Asia-Australia and Europe-Africa) and four tasks.

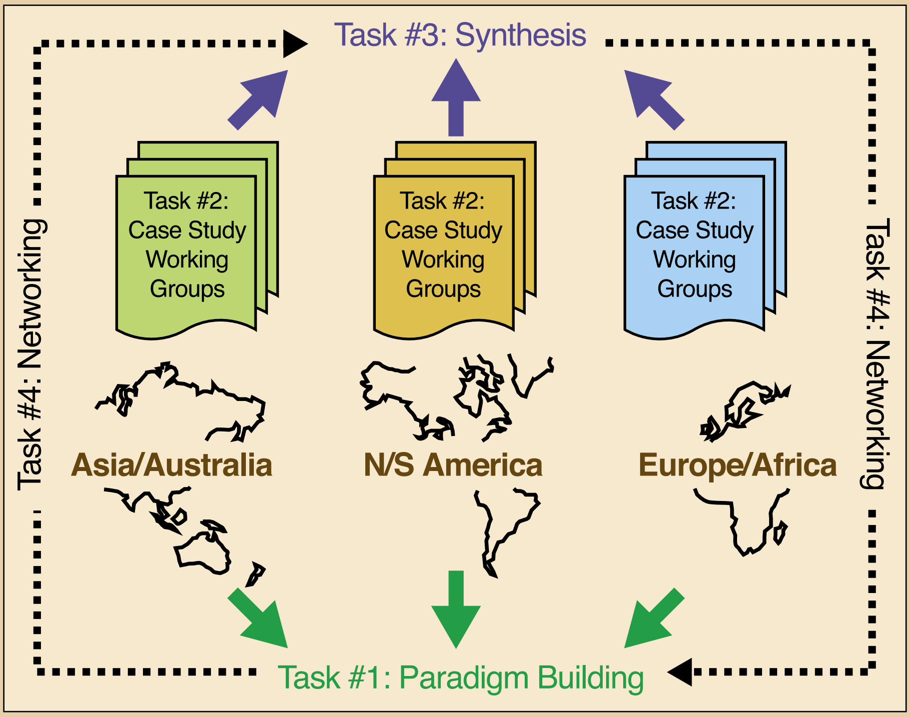


Figure 9. The three nodes and four tasks of ARIDnet. From Reynolds et al. (2003).

Task 1 is Paradigm Building. Using workshops and symposia, a conceptual, hierarchical model of land degradation – the Dahlem Desertification Paradigm (DDP), see www.biology.duke.edu/aridnet and Reynolds and Stafford Smith (2002) – is being critiqued, applied and revised by the international community of desertification researchers, stakeholders and policy-makers. The DDP is an invaluable tool because it: (i) highlights key linkages between socio-economic and biophysical systems at different scales within a single synthetic framework; and (ii) is testable, thus enabling improvements.

Task 2 is Case Studies. Working groups are testing the DDP using case studies selected in a stratified, comparative manner to represent a wide range of biophysical and socio-economic settings throughout the world. These case studies are based on existing data and specific stakeholders. The first case study was of the small rural community of La Amapola in central Mexico. Application of the DDP identified key socio-economic and biophysical variables involved in land degradation in La Amapola, and identified potential restoration options.

Task 3 is Synthesis. Case studies will feed into a quantitative assessment of what really matters in desertification, especially interactions between key biophysical and socio-economic variables.

Task 4 is Networking. ARIDnet strives to recruit and foster the participation of a diversity of researchers.

soil degradation, sulphates from urban systems), aerosol transportation patterns and their climatic effects, and precipitation states and efficiency. Important questions include: (i) do urban heat islands impact downwind ecosystems?; (ii) is widespread irrigation increasing humidity and disease vectors in arid areas?; and (iii) when groundwater-based irrigation is depleted, will ecosystems recover under the original climates?

It is the singular and multiplicative effects of atmospheric changes and their feedbacks within terrestrial and freshwater ecosystems that will be the focus of activities in this area. Additionally, the wide array of existing case studies needs to be compiled and organised into temporally consistent and spatially geo-referenced databases for full impact assessment. It will be important to go beyond quantifying rates of land cover change, by undertaking an integrated analysis that represents the policy and economic decision making that control land use changes.

Summary

- Focuses on closing key biogeochemical budgets for a wide variety of systems, at different spatial and temporal scales, and under the influence of interacting global change drivers.

- Builds on a decade of research to understand how different elements of global change affect ecosystems at local to regional scales.

- Emphasises variability, extreme events and non-linear or threshold-based responses to global change.

- Considers the impacts of toxins and pollutants in perturbing biogeochemical cycles and the consequent impacts on environments and human health.

- Provides the basis for Theme 2 considerations of how global change will affect ecosystem services, and prioritises the ecosystem services considered in Theme 2.

Contributing Community

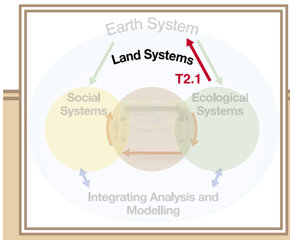
Agricultural research community, atmospheric science research community, iLEAPS, water resources community, DIVERSITAS, BioMerge, TERACC, Biosphere-Atmosphere Stable Isotope Network (BASIN), FluxNet, Past Global Changes (PAGES).

Theme 2: Consequences of Land System Change

The consequences of land system changes brought about by land use and global environmental changes, including feedbacks between people and ecosystems, are critical to Earth System science. Feedbacks to people are understood as changes in the delivery of a broad range of ecosystem services, such as agricultural productivity, clean air, potable water and many others. Feedbacks to ecosystems are understood in terms of changes in regimes of decision making related to land management, and may also include the feedbacks of societal changes to these processes. These changes may be induced by actual or perceived land system changes, or may be mediated through the effects of broader social, demographic and economic forces in shaping local land use decisions.

Changes in the availability of ecological services affect the viability, productivity and stability of the coupled socio-environmental system on which humans rely. Land management decisions may result in trade-offs in the delivery of different ecosystem services. The objectives of this theme are therefore to identify possible trade-offs in land use decisions, and to comprehend their multiple and complex causalities and the consequences they impose on land management. Effort will be made to quantify changes in ecosystem services caused by alterations of disturbance or management regimes, as these may induce shifts in land productivity by modifying physical inputs and economic returns.

The relationship between human activities and the conditions of the resource base cannot be mapped in terms of simple cause-effect paradigms. While technical knowledge or even optimal solutions may be available to respond to land system changes, actual decision processes will be influenced by economic, social, political, cultural and even psychological factors, and will involve negotiations and conflict resolution. Social differentiation and social dynamics have proved critical in influencing both decisions on the management of resources, and responses to environmental changes. There may be fundamental differences in the perception of changes, which are equally consequential for attitudes, knowledge, preferences and behaviour. Theme 2 research will need to integrate the complex socio-economic, political and cultural environmental characteristics in which land use decisions are embedded, and conceptualise these decisions in the context of patterns and processes at various scales. In many places, the crucial relationships characterising land systems are studied at a local or regional scale, yet a fundamental challenge for GLP remains that of understanding how these relationships are affected by, and have implications for, the global scale. A number of the key factors for decision making processes may also change over time. Hence, the temporal dimension will also be an indispensable element for a comprehensive analysis of the interactions between societies and their environment. The ultimate goal is to better inform the process of defining sustainable land management strategies.



Issue 2.1: What are the Critical Feedbacks to the Coupled Earth System from Ecosystem Changes?

As a result of direct (e.g. land use change) and indirect (e.g. atmospheric and climate change) effects of human activities, terrestrial and freshwater ecosystems are being altered. When ecosystem structure or functioning is altered, this is likely to alter biogeochemical cycles and the biophysical properties of ecosystems, including in particular, fluxes of carbon, nutrients, water and energy. Because of the importance of these fluxes in influencing regional and global atmospheric chemistry and climate, there will be significant feedbacks to the Earth System. For example, positive feedbacks (reinforcing human-caused climate change) will occur if the flux of carbon and other greenhouse gases from ecosystems to the atmosphere is increased, or if changes in the surface properties of ecosystems cause local or regional warming. Negative feedbacks (reducing net climate change) will occur if terrestrial ecosystems store more carbon. It is critical to determine the extent to which ecosystem changes will feed back to the Earth System. Different ecosystems and regions may respond in different ways, so that region-specific analyses are essential in addition to the global-scale feedbacks that will be simulated in Earth System models.

Research in Issue 2.1 will focus on the implications of land change for the functioning of the Earth System, and build extensively on research conducted in Theme 1. However, research specific to Issue 2.1 will deal with the manner in which land feedbacks are affected by the ecosystem changes due to human activities and environmental change. Thus, this set of research activities emphasises: (i) interactions of multiple stresses on ecosystem feedback; (ii) landscape scaling across time and space (from the patch scale to the global scale) and across land use management types; and (iii) integrative studies to link with other groups in ESSP.

Critical Earth System Feedbacks

Issue 2.1 deals primarily with the effects of changing ecosystem dynamics on the Earth System, due to changes in vertical and lateral fluxes. GLP will contribute to understanding the changes that are occurring to global biogeochemical cycles, including the natural and human dimensions of these changes. These changes include direct emissions of various trace gases to the atmosphere, and a large number of indirect emissions of gases to the atmosphere and riverine transport of materials to the coastal zone arising from human-driven changes to land systems. Agro-ecosystems and urban areas are extremely important components of the land system in terms of their potential impacts on the Earth System, and yet the biogeochemistry of these systems has not been adequately studied.

While most feedbacks result from relatively slow but directional changes in ecosystem physiology, abrupt changes are also possible and can involve thresholds in the functioning of terrestrial ecosystems. For example, climate change and land use change have the potential to cause relatively rapid alterations in ecosystem structure or function, which in turn have significant effects on the Earth System.

Issue 2.1 research will investigate the effects of various atmospheric and climatic factors (e.g. increased carbon dioxide concentrations, warming and altered precipitation) on ecosystem structure and function, and will be closely linked with modellers developing improved dynamic ecosystem models. Landscape changes can alter freshwater aquatic ecosystems due to changed lateral fluxes of water and materials, in turn leading to feedbacks from these freshwater systems. Studies of the mechanisms and magnitudes of fluxes of water, nutrients and sediments from land to water are needed for different regions at a variety of scales.

Fire regimes and other disturbances (e.g. vertebrate and invertebrate herbivory) are influenced by a wide range of human activities, from direct management interventions to indirect impacts of climate change. Animals (e.g. herbivores, pollinators and seed dispersers) regulate the structure and functioning of terrestrial ecosystems, and can thus be indirect determinants of a landscape's ability to store carbon and nutrients. By combining research on the causes and consequences of fire and other disturbances in various regions with global modelling efforts, research in Issue 2.1 will identify critical thresholds and hot spots of fire and grazing regimes in Earth System function.

Critical gaps include: (i) how do land use and land management change alter river discharge (quantity, quality and timing)?; (ii) how does carbon leach from uplands to rivers and how important is this for the global carbon budget?; (iii) how does sediment transport vary among major river systems and what is the role of humans in altering sediment flux?; (iv) what are the biogeochemical functions of wetlands?; (v) how have changes in fire regimes affected the biogeochemical and biophysical characteristics of ecosystems?; and (vi) how have changes in animal dynamics affected transfers of energy, water and nutrients across landscapes, and what are the regional feedbacks to the Earth System?

Relationships in Space and Time Affecting Ecosystem Feedbacks

Spatial patterns of land cover, land use, soils and topography can affect how processes interact and scale up to affect the Earth System. For example, studies indicate that the response of rainfall to deforestation can be non-linear, depending on deforestation patterns (Goitre et al., 1997). Modelling and observational studies need to address the influence of spatial patterns and landscape heterogeneity on processes, including non-linear responses and the possibility of abrupt changes. Several critical questions remain unanswered: (i) what are the controls on how landscape patterns influence material and energy fluxes from the land?; (ii) what spatial resolution of land cover and land use data is required to adequately represent the impacts on lateral and gaseous

Box 7. Ecosystem Goods and Services

Earth System processes provide environmental goods and services that sustain life and are essential for human well-being. These "ecosystem goods and services" include potable water, fertile soil, clean air and flood mitigation. Throughout history these have largely been taken for granted, because they were not significantly affected by human activities. As a result, most economic institutions have inadequate ways of valuing ecosystem goods and services, most of which are not traded in the market place. The magnitude of the human impacts on the environment – including direct effects on biogeochemical cycles, now threatens the quality and long-term delivery of ecosystem goods and services.

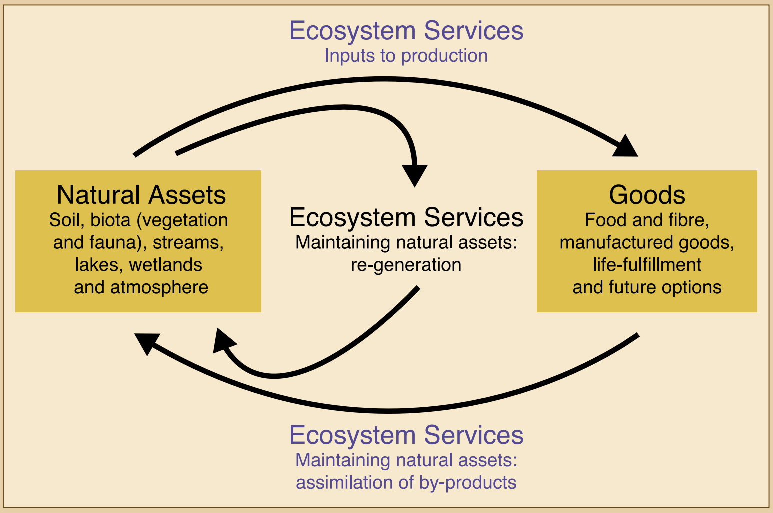


Figure 10. The relationships between ecosystem natural assets and ecosystem goods and services. From ASEC (2001).

fluxes?; and (iii) are responses more sensitive to changes in spatial patterns in some regions of the world than others?

Various scaling methodologies exist for biophysical processes (Feddes, 1995; Moorcraft et al., 2001; Avissar and Chen, 1995; Norman, 1993; Box, 1996); however, scaling research by ecologists has not considered socio-economic systems, and social scientists have not adequately considered ecological processes. Feedbacks from the land system to the Earth System are non-linear and operate through complex processes that are not yet well understood or quantified. The challenge for GLP is to fully develop new scaling methodologies within a coupled socio-environmental system. This will involve the development of new models and observational systems for model testing (Running et al., 1999).

The scope of biogeochemical studies of land systems will be expanded, with priority being given firstly, to urban and peri-urban areas, and secondly, to extensive and intensive agro-ecosystems (including cropping, grazing and mixed systems). The ultimate goal of these studies is to close system budgets for carbon, nitrogen and phosphorus, at the local, or if possible, regional level, accounting for inputs (e.g. fertiliser applications), outputs (to the atmosphere and freshwater systems) and internal accumulation or depletion (including chemical transformations).

Complete closure of biogeochemical budgets is relatively rare, even in well-studied ecosystems, partly as there is still great uncertainty regarding the fate of carbon and nitrogen in terrestrial and freshwater systems (Hungate et al., 2003). Although there is now convincing evidence for a large terrestrial carbon sink, there is little consensus on sink location or responsible processes. Similarly, reactive nitrogen is hypothesised to be accumulating in land systems, but the evidence is weak and sometimes contradictory. Closing budgets for carbon, nitrogen and phos-

Box 8. Urban Carbon Dioxide

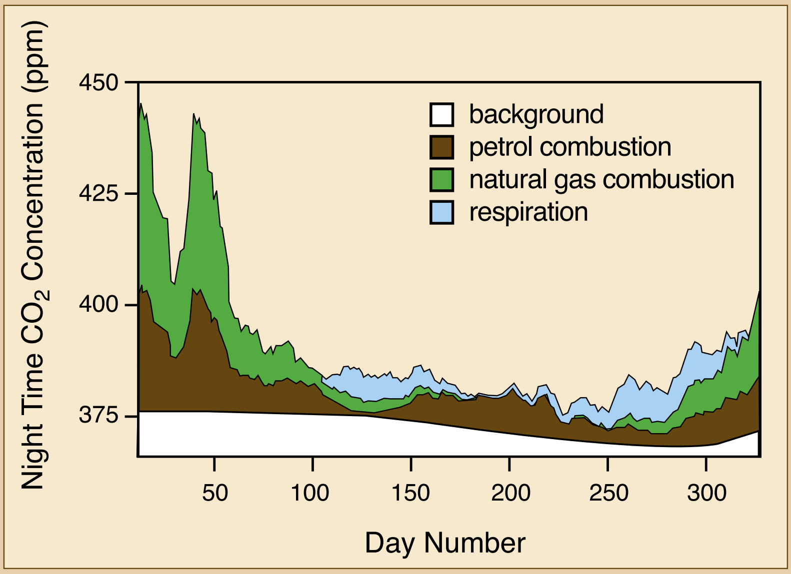


Figure 11. Partitioning of 2002 night time carbon dioxide concentrations for Salt Lake City, Utah. From Pataki et al. (2003).

Human-dominated land systems such as cities, are still significantly influenced by ecological processes such as plant and soil biogeochemistry. The Biosphere-Atmosphere Stable Isotope Network (BASIN) initiated within GCTE uses isotopic tracers to detect the influence of ecosystem processes on the atmosphere, and to determine how these processes are modified by global change.

Carbon isotope measurements in Salt Lake City, Utah, USA were used to separate night time carbon dioxide concentrations into a biogenic component from urban forest respiration and anthropogenic components from fossil fuel burning. The results show that despite the large influence of fossil fuel emissions on the urban atmosphere, biological processes are easily detectable. These processes contribute to the urban carbon cycle and provide a variety of services for urban residents, including carbon sequestration, removal of atmospheric pollutants, and the cooling effects of transpiration and altered albedo.

phorus for a spectrum of land systems will greatly help in reducing these uncertainties, and improve the understanding of the interactions of biogeochemical cycles.

Current research in the Yaqui Valley, Mexico, offers a powerful model for biogeochemical budget determination for complex, regional-scale, human-dominated systems. Proposals for studying the biogeochemical cycling of urban ecosystems should be important contributors to this GLP research activity. FluxNet offers another technique to evaluate biogeochemical budgets, although few FluxNet sites also study the lateral movement of elements. It is therefore proposed that new networks be established for different land systems, which can build upon model studies that are already underway. It is important that a common, basic methodology be followed to enable budget comparisons, and to facilitate the scaling up of results from local and regional scales to the global scale. Integrated studies of stores and fluxes of major biogeochemical cycles in various ecosystems and the role of human activities in altering these budgetary compartments, should deliver useful data sets for testing regional and global land system models.

Summary

- Improves process-level understanding of land system biogeochemistry (including urban and agro-ecosystems), particularly the effect of multiple stressors on processes affecting material fluxes.

- Improves understanding of the dynamics of lateral fluxes of carbon, water, nitrogen and sediments, and their roles as feedback pathways to the Earth System.

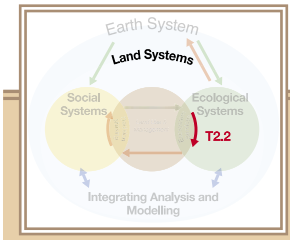
- Evaluates changes in disturbance regimes (fire and grazing) and ecosystem feedbacks resulting from land management and altered climate.

- Improves models to scale up biogeochemical fluxes from local and regional to global scales.

- Aims to close regional carbon, nitrogen and phosphorus budgets for a spectrum of land systems, in particular urban, peri-urban and agricultural ecosystems.

Contributing Community

GCTE, AIMES, iLEAPS, LOICZ, TERACC, BASIN, FluxNet, Biosphere-Atmosphere Trace Gas Exchange (BATREX), LUCC, GCP, GWSP, IDGEC.



Issue 2.2: How Do Changes in Ecosystem Structure and Functioning Affect the Delivery of Ecosystem Services?

Ecosystem structure and function are not equivalent to ecosystem services. Mooney (2003) made considerable progress in defining ecosystem services, and the linkages between ecosystem services and ecosystem structure and function. Issue 2.2 will build on this work to explore how changes in ecosystem structure and functioning affect the delivery of ecosystem services. Many ecosystem studies to date have focused on a few ecosystem properties (e.g. primary productivity and nitrate leakage), but have not been followed through to specific ecosystem services (e.g. carbon sequestration and water quality). Hence they have not helped assess the potential impacts of climate, atmospheric composition or land cover change, on the variety of services provided by mosaics of ecosystems managed at different intensities. Thus it has not been possible to consider how such impacts affect land use and land management trade-off decisions. The primary focus of Issue 2.2 will be on the development of a robust analytical framework and methods to assess changes in the delivery of ecosystem services, using measurements or simulations of changes in ecosystem structure and functioning and their relationships to land management.

Assessing the nature of the consequences of land management change in a given context requires the integration of various types of scientific knowledge. For example, knowledge of the responses of a broad range of services provided by a given land cover type to change (including shifts between land cover types). The goal is to provide an important part of the basis for these complex management decisions by synthesising knowledge and identifying knowledge gaps. This will be of particular interest in identifying land management pathways that can lead to trade-offs or synergies amongst services.

Issue 2.2 will focus on changes to a subset of ecosystem services defined by the MEA that have high value at the global or local scale, and that can be addressed using Theme 1 research. These ecosystem services include: food and fibre provision, water quantity and quality regulation, climate regulation through biophysical properties or greenhouse gases fluxes, soil quality regulation, stability and regeneration capacity, and other services that have high value in specific systems (e.g. provision of medicinal plants to indigenous peoples in tropical regions). It will be important to develop appropriate metrics and measures of these changes.

Improved understanding of which ecosystem properties and processes contribute to the delivery and maintenance of specific ecosystem services is required, underpinned by a sound theoretical basis for proposing hypotheses of the ecological mechanisms that underlie interactions, trade-offs and synergies amongst ecosystem services. These hypotheses should be tested with data from existing studies where a range of services has been quantified simultaneously. Special attention should be given to identifying critical non-linearities and feedbacks that can cause abrupt change in ecosystem service provision. Such results would guide management by providing indications of ecologically incompatible demands, for example, by identifying trade-offs between different ecosystem services when a single focus land management perspective is taken.

Drivers of Ecosystem Structure and Function Change

The effects of multiple (both biophysical and socio-economic) drivers of ecosystem structure and function change need to be assessed at various spatial and temporal scales. Examples of drivers are: (i) global biophysical or biogeochemical change, for example, climate and atmospheric carbon dioxide concentrations; (ii) institutional change, for example, administrative decentralisation; (iii) management practice changes , for example, abandonment of intensively cropped systems; and (iv) societal transformations, for example, from centrally-controlled to free-market economy.

It is inadequate to solely use observed differences between existing land cover types to estimate the changes that will occur following land cover conversion, because of the time scales of response. For example, soil changes following cropland or pasture abandonment are considerably lagged, with very slow subsequent recovery in carbon sequestration or supporting services by older forests (Foster et al., 2003). Research will therefore focus on the most common land use trajectories for different regions of the world.

To achieve global coverage, syntheses should be undertaken for a variety of global-scale land cover categories. Additionally, syntheses should be undertaken for finer-scale land cover categories (with the inclusion of site-specific ecosystem services) using a selected set of local or regional studies. Questions on how the delivery of multiple services by various land covers is affected by these changes will need to be addressed through a combination of analytical approaches, with various types of experiments, observation techniques and models. Studies will need to include evaluation of the natural variability in the provision of key services for various land cover and land use types. Undeniably, the study of the most complex combinations of changes will lead to the concentration of scientific efforts in a few locations where intensive process research is conducted (cf. Issue 1.3).

A major task in this context will be to understand how shifts in land cover and changes in land use intensity, can alter the delivery of ecosystem services in qualitative and quantitative terms. This includes understanding how the delivery of ecosystem services changes following catastrophic disturbance, or unusual series of disturbances.

Connectivity of Ecosystems Across Scales

A major challenge will be to analyse the connectivity of different ecosystems across scales, and the manner in which connectivity affects the vulnerability of service delivery under stresses caused by changes in external or internal natural or socio-economic variables, or unusual series of disturbances. The capacity of a single patch of land to produce a variety of ecosystem services is affected by its landscape context, as this modifies local ecosystem functioning. In many cases, ecosystem services at the landscape scale cannot be deduced by summing the services provided by individual land cover types. This is because firstly, there can be considerable heterogeneity within a land use type; for example, localised changes in carbon sequestration potential may result from differences in topographic location, soil texture and water regime. And secondly, land use mosaics can affect the delivery of ecosystem services by determining biotic interactions and fluxes of matter, energy and information across the landscape. In agro-ecosystems, for example, an understanding of changes in net regional productivity (allowing for complex land use patterns and interactions) rather than just plot-scale productivity is needed to resolve issues related to food security.

The role of landscape connectivity and landscape dynamics in ecosystem service delivery is not sufficiently understood. Studies need to address how different patterns of land cover and land management affect the capacity to deliver a service, or lead to the spread or expansion of pests and diseases. Especially important in this context are studies in areas undergoing rapid transformations: for example, peri-urban areas or areas of agricultural intensification. Understanding connectivity of different ecosystems across scales is linked to the issue of multiple element budget closure within a region (Issue 2.1).

Summary

- Develops a robust analytical framework and methodologies to assess changes in the delivery of ecosystem services, using measurements or simulations of changes in ecosystem attributes (structure and function), and development of appropriate metrics and measures of these changes.

- Develops clear hypotheses about ecological mechanisms that underlie interactions, trade-offs and synergies among ecosystem services, and tests them against existing data.

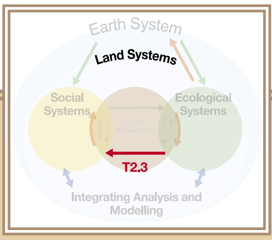
- Assesses the effects of multiple (biophysical and socio-economic) drivers of change in ecosystem structure and function at various spatial and temporal scales, with special attention to non-linearities and feedbacks.

- Seeks to understand how shifts in land cover and land use intensity (including effects from catastrophic or unusual series of disturbances) alter the delivery of ecosystem services in qualitative and quantitative terms.

- Analyses the connectivity of different ecosystems across scales, as well as the role of landscape connectivity and landscape dynamics in the delivery and vulnerability of various ecosystem services.

Contributing Community

MEA, DIVERSITAS, TERACC, BASIN, FluxNet, IGBP Transects, iLEAPS, LOICZ, GCP, GECAFS, Global Environment Change and Human Health (GECHH).



Issue 2.3: How are Ecosystem Services Linked to Human Well-being?

Human well-being depends on a wide range of goods and services provided by terrestrial ecosystems. These have a vital role in the supply of economic goods as well as sustaining, regulating and supporting life on Earth (Costanza et al., 1997; Daily, 1997; Daily et al., 2000). Human reliance on ecosystem services extends well beyond economic welfare (encompassing income, assets and capabilities), to health, security, food and nutrition, as well as cultural identity, aesthetics and spirituality. Changes in land systems can alter their capacity to deliver services, degrade the quality of services and threaten the resilience of ecosystems. Issue 2.3 seeks to understand how human well-being will be affected by such changes.

A critical issue for GLP is how particular changes in ecosystem services actually affect human livelihoods in any given context. This combines much previous research on how natural and anthropogenic environmental change affects human populations, economies and societies. Whereas many studies seek to document how extreme events (e.g. drought, hurricanes and pest invasions) and ecological disturbances affect life, livelihood and vulnerability, or speculate on the effects of anticipated global environmental change, few studies as yet provide controlled comparisons or natural experiments contrasting conditions before and after abrupt shifts in the provision of suites of ecosystem services (Turner et al., 2003). How, for example, do changes in the delivery of ecosystem services affect agricultural productivity, the economics of agriculture (participation, cost-price conditions, economic returns and investment), rural livelihoods and migration, conflicts over land and water, and public health and security?

Studies are also needed to track site-level changes in the value of ecosystem services across different states of ecological disturbance, and to document the effects of changes in multiple ecosystem services over time. This will require comparison of case studies to evaluate the level of well-being dependency on ecosystem services for different land systems under different socio-economic conditions, and to identify and assess the factors affecting the stability of the relationship between ecosystem function and human well-being.

Ecosystem Services in the Context of Livelihood Systems

In order to assess their significance for human well-being, ecosystem services need to be translated into the contexts of various livelihood systems. Livelihoods not only entail meeting basic food, nutrition and income needs, but also building the assets and capabilities that condition the prospects for well-being. A growing literature on sustainable livelihoods points to the need to better link multiple ecosystem services and functioning with asset formation and income generation. The reliance upon natural resources by rural producers, from agriculture to the harvesting of forest products, is well known in principle, but requires further study to value the resources and assess the sensitivity of the relationship between livelihoods and ecosystem services to changes in land systems.

Whereas consumptive goods provided by land systems (e.g. grains, animal protein, and fibre and wood products) are typically valued through markets, the contributions to human well-being and ecosystem functioning of the underpinning services provided by ecosystems often remain invisible and unvalued (or undervalued). Biodiversity for instance, can be seen as the "glue" that holds nature's structure and processes together, and is highly significant for maintaining ecosystem functions upon which human well-being depends. But it is very difficult to value the extent and varying degree to which economic livelihoods directly or indirectly depend on biodiversity. A growing recognition of the importance of indirect ecosystem services for households, communities and industries in urban centres, suggests the need to consider not only the primary sector, but also the links to secondary, tertiary and quaternary sectors, of local, regional and national economies.

Valuation of Ecosystem Services

The concept of "value" in studies of nature is controversial. Notions of "value", "value systems" and "valuation" have distinct meanings and interpretations across disciplines in the natural and social sciences, most notably in economics and ecology, but also in psychology, philosophy, sociology, anthropology and political science (see Faber et al., 2002). The very bases of valuation may also differ between cultures or social groups. The multiple dimensions of social difference (e.g. age, gender, wealth, class and race) and their changes over time influence the valuation of ecosystem services. Just as the access to, and dependence on, certain services is distributed unequally, the impacts of environmental changes are also felt unevenly. Thus, even though the contribution of ecosystem services to ecosystem functioning might follow consistent principles at the global scale, their contribution to human well-being may be rather heterogeneous, because people benefit in different ways from their delivery.

Any attempt to value ecosystem services thus needs to take account of how the benefits and costs of their use are distributed across different social groups, and consider what determines the control of access to, and management of, ecosystem services. The scale of observation is critical in such analyses. Typically, local users highly value the direct (use) products provided by ecosystems in the near term, while more distant communities place more value on the indirect services (regulating, maintaining and supporting functions) provided by ecosystems over the longer term. The spatial and temporal separation of costs and benefits across social groups is evident in a wide range of contexts: from local to global; from upstream to downstream users in catchments; between rural and urban dwellers; and across socio-economic groups of differential wealth, power and vulnerability. In developing countries the local costs of ecosystem preservation are high for the sake of potentially large global benefits. In more industrialised countries local costs may be relatively low for modest global benefits (Turner et al., 2003). Such analyses of the distribution of benefits and costs of ecosystem service use across social groups is fundamental to policy discussions aimed at reducing social conflict and furthering social equity, as well as to considerations of ecological sustainability (e.g. through international compensation or 'pay for ecological services' schemes).

Metrics and Measures of Land-based Ecosystem Services

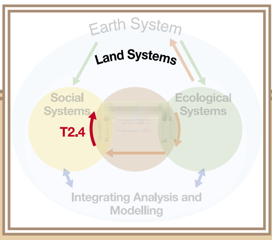
In order to develop new valuation metrics and measures of land-based ecosystem services, much research is needed to provide the theoretical and methodological foundations for valuation. A systematic exploration of the full range of approaches to, and typologies for, the problem of ecosystem service valuation is needed to provide a cross-disciplinary perspective for natural and social scientists that accounts for this pluralism. Of particular importance are studies that seek to assess the full complement of functional uses and non-use values (i.e. beyond single ecosystem functions to multiple functions and uses), with a specific focus on values that affect, and are affected by, cross-scale factors that can only be elucidated by studies across regions and scales.

Summary

- Provides comparisons and experiments to contrast conditions before and after abrupt shifts in the provision of suites of ecosystem services.
- Calls for comparisons of case studies to evaluate the level of well-being dependency on ecosystem services for different land systems under different socio-economic conditions.
- Identifies and assesses the factors affecting the stability of the relationship between ecosystem function and human well-being.
- Systematically explores the full range of approaches to, and typologies for, the problem of ecosystem service valuation.
- Analyses the distribution of benefits and costs of ecosystem service use across social groups.
- Seeks to develop new valuation metrics and measures of land-based ecosystem services (including a full complement of functional uses and non-use values).
- Works on the theoretical and conceptual foundation for the valuation of land-based ecosystem services (including indirect ecosystem services).
- Assesses the sensitivity of the relationship between livelihoods and ecosystem services to changes in land systems.

Contributing Community

DIVERSITAS, TERACC, BioMerge, National Science Foundation (NSF) funded Biocomplexity Initiative, MEA, PAGES, GCP, GECAFS, IDGEC, Geostationary Earth Climate Sensor, IT, Integrated Pollution Prevention and Control, Common Property Network, BATREX, GECHH.



Issue 2.4: How Do People Respond at Various Scales and in Different Contexts to Changes in Ecosystem Service Provision?

Humans have sought for millennia to manage the natural resources derived from terrestrial ecosystems upon which they depend for their livelihoods and well-being. A large body of environmental science and policy, developed most fully over the past three decades, focuses attention on the management of lands, forests and other resources, pointing to the importance of considering the dynamic ecological processes that provide the specific economic and non-economic products of interest. With a growing appreciation of the importance of ecosystem services and functions, a significant shift in the focus of environmental management is underway, from natural resources to ecosystem services and functions. Such a shift requires an improved understanding of the links between managed ecosystems and how people respond or adapt to changes in service provision, given the various scales and contexts of decision making. This includes the need to analyse how human agency feeds back on these changes.

The delivery of ecosystem services and their context cannot be viewed independently. Any change in ecosystem attributes or any response to these changes may have positive or negative consequences, depending on the spatial, temporal or socio-cultural context in which the consequences occur or are evaluated. For example, agricultural intensification may be motivated by expected benefits for parts of the local population, yet can result in adverse effects for other social groups, or in other places or times. At a landscape scale, however, increases in productivity might also permit the allocation of land to protected areas, thereby enhancing biodiversity, providing recreation or aesthetic benefits and other positive consequences at that particular scale.

Issue 2.1 considers this notion from the perspective of the relationship between ecosystem functioning and human well-being for different land systems. In Issue 2.4 however, it is important to also acknowledge that land use decisions are often imbedded in complex, layered systems related to different driving factors on different scales. Management strategies entail equally complex and pervasive trade-offs that differentially affect a wide range of social groups. Progress needs to be made in understanding how to balance the positive and negative effects of changes in ecosystem structure and function in a given context as a basis for sustainable land management.

Critical Feedbacks and Threshold Shifts in Land Systems

Recent efforts within LUCC (Focus 1) have helped to unravel the underlying biophysical and human characteristics associated with different magnitudes of deforestation and forest recovery, such as the level of farmer education, population size and distribution, resource use alternatives, and the degree of depletion of biotic resources through previous land use (see Geist and Lambin, 2001). Further work is required to determine the feedbacks between global environmental changes, alterations in ecosystem structure and function, and key land use and land cover changes. Of particular concern are 'threshold shifts' or triggering effects among different land systems, and critical feedbacks between ecosystem change and land use, land cover and land management. This includes rapid and extreme transitions in natural and socio-economic properties of a coupled system. Because social groups rely on ecosystem services to differing degrees and hold uneven wealth and power, they are likely to be affected heterogeneously by such transitions (e.g. land-poor versus land-rich; rural versus urban dwellers; upstream versus downstream land owners). Levels of vulnerability must be assessed across land user and non-user groups, and changes in ecosystem services must be linked with societal factors such as migration, institutional change and socio-political conflict. This includes the need to understand what will promote the capacity of social actors and communities to adapt to natural and anthropogenically driven shifts in the provision of ecological services.

Societal Responses to Environmental Changes

From these concerns emerge the issue of what strategies different social groups use to deal with changes in ecosystem services, and what the consequences of these strategies are over time. A primary focus here is to understand the integrated and recursive nature of the link between land use behaviour and global environmental change. Global environmental change affects the local delivery of ecosystem services, and feeds back to land use and land cover change through land users' decisions. Humans are active agents that seek to find appropriate responses to perceived changes in critical environmental variables. Different social groups deploy distinctly different strategies in seeking to secure and maintain access to, as well as protecting, the ecosystem goods and services upon which that their livelihoods rely. Land management therefore entails a complex interplay of factors that influence land users' decisions, which in turn, are reflected in land cover changes. For example, changes in monsoon regimes in southern China, due in part to land cover changes, are forcing farmers to adopt new land use strategies, which will in turn affect land cover and the monsoon itself. Awareness of a coming El Niño event, from meteorological forecasts or traditional knowledge, affects farmers' cropping decisions and thus land cover changes, and therefore the consequent potential for fire. This in turn, conditions subsequent land use behaviour, with distinct land cover outcomes. Out-migration due to land degradation in the Sahel changes labour availability for agriculture (as do diseases, including Acquired Immuno-Deficiency Syndrome), while remittances from migrants condition the prospects for local investment in livestock, affecting land cover and ultimately the fate of desertification.

Among the more difficult trade-offs are those between local land-based economic and social development and regional-national-global nature conservation. For example, the preservation of tropical rainforests, while promising significant aggregate global ecosystem service benefits, imposes potentially high costs on local farmers. Upstream users may diminish the quality and availability of ecosystem services (including system resilience) which support service provision for downstream users. Certain types of urban development can compromise the ecological basis of cities, differentially impacting upon the social groups therein, but also forcing trade-offs with rural dwellers, particularly in peri-urban environments. The protection of natural capital is traded off against the restoration or substitution of natural capital, with human-made technological alternatives for the provision of ecosystem services. The potentials and limitations of such substitution need to be carefully examined.

There is also a lack of understanding of the embedded nature of such trade-offs. Assessments need to advance efforts to reconcile dilemmas and conflicts over ecosystem services, and promote ecological sustainability and social fairness. But they also need to take into account the diversity, flexibility and ambiguity of human choices, and the fact that human-induced processes have a strong 'random' element. In-depth analyses of the use of natural capital tend to unravel fundamental societal conflicts and power relations (e.g. entitlements), as the respective decision pathways are structured by a process of societal negotiations regarding the question of what trade-offs are acceptable where, when and for whom.

Land management decisions might therefore depend as much on the distribution patterns of benefits and costs in given political and socio-economic contexts, as on the knowledge and expectations about potential impacts of certain behaviour on the natural resource base of human well-being. They also depend on how knowledge is generated, accumulated, distributed and mediated. Any comprehensive evaluation of sustainable development pathways needs to relate explicitly to careful analyses of the underlying power relations governing the process of environmental appropriation and negotiation, and the rationales and practices of power in given contexts. Appropriate ways need to be found to reconcile such complex socio-political and socio-cultural processes with rigorous modelling approaches.

Complex and Multi-layered Institutional Systems

These issues are particularly relevant for the development of a research framework for the multiplicity of scales involved in global environmental change. Land use decisions are imbedded in a complex, multi-layered system of institutions at different scales. Institutions are understood as common sets of rules and norms of conduct that play a key role in mediating and facilitating the use of natural resources. It is crucial to explore how efficient various institutions are in managing changes in the delivery of ecosystem services and ecosystem management trade-offs. Institutions of particular importance for land systems include market regimes, property right regimes, social networks, state political regimes and government bureaucracies, and environmental management policies and programmes on different scales. A large body of literature examines the role of institutions in resource management (usually under stable environmental conditions), though interest is growing in endogenous institutional change in response to environmental change, and in the interaction between rapid transformations of institutional settings and their impact on land systems.

As environmental management efforts focus increasingly on ecosystem services (rather than single resources or uses), new institutional arrangements and processes will be needed that are capable of harmonising benefit streams from multiple ecosystem functions across a range of different social groups (PNAS, 2003). This will include mapping and evaluating existing institutions that specifically manage the provision of ecosystem services, and assessing their performance in effectively maintaining and managing multiple and indirect ecosystem services at different scales. Considerable research will be required of both social and natural scientists to support the development of flexible ecosystem service institutions capable of responding to global environmental change. Furthermore, under conditions of global environmental change, there will be an increasing requirement for institutions that provide mechanisms and procedures to mediate and resolve conflicts among social groups over the use and management of ecosystem services.

Summary

- Evaluates the level of well-being dependency on ecosystem services for different land systems under different socio-economic conditions, and identifies the factors affecting the stability of the relationship between ecosystem function and human well-being.

- Encourages the comparison of site-level studies of changes in the value of ecosystem services across different states of ecological disturbance, and the documentation of the effects of changes in multiple ecosystem services over time.

- Attempts to unravel the underlying biophysical and human characteristics associated with thresholds and the critical feedbacks between ecosystem change and land use, land cover and land management among different land systems (including rapid and extreme transitions in both the natural and the socio-economic properties of a coupled system).

- Analyses the complex and multi-layered conditions of decision making related to changes in ecosystem structure and function, and contributes to a learning process that considers how to balance the positive and negative effects of these changes and their management in a given context as a basis for sustainable land management.

- Analyses the strategies of various social groups for dealing with changes in ecosystem services, assesses vulnerability across these groups, and links changes in ecosystem services with societal transformation, institutional change and socio-political conflict.

- Explores how to reconcile socio-political and socio-cultural reasoning with rigorous modelling practice.

- Analyses and evaluates existing institutional settings at different scales, and assesses their efficiency in managing the provision of ecosystem services and in resolving conflicts over the use and management of ecosystem services.

Contributing Community

DIVERSITAS, TERACC, EU Framework Programme 6 networks, BioMerge, NSF funded Biocomplexity Initiative, GCTE Focus 3, MEA, GCP, GECAFS, IDGEC, GECHS, IT; Urbanisation, LOICZ, Common Property Network, BATREX.

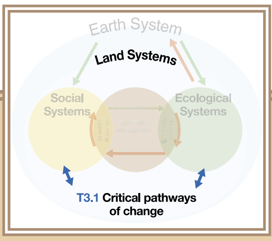
Theme 3: Integrating Analysis and Modelling for Land Sustainability

Themes 1 and 2 provide the building blocks for Theme 3, which examines the combined effects upon the broader Earth System of feedbacks that occur through biogeochemical cycles, biodiversity and natural disturbance regimes, as well as feedbacks in response to land ecosystem change. Theme 3 seeks to integrate the dynamic interactions of human and environment subsystems in order to assess vulnerability, resilience and adaptation towards sustainable land systems, and specifically aims to provide this understanding in ways that are meaningful to decision making and policy. To accomplish this, Theme 3 will integrate findings from Themes 1 and 2 and from related projects of IGBP, IHDP, DIVERSITAS, MEA and other programmes.

Diverse scientific studies have provided a rich foundation on which integrated analyses can build. Research has highlighted the roles of emergent and path-dependent properties of coupled socio-environmental systems, and the thresholds in these complex systems that change their structure and function (e.g. Berkes and Folke, 1998; Holling, 1978; Levin, 1998; Schellnhuber and Wenzel, 1998). Work on vulnerability, resilience and ecosystem services has demonstrated the nature of threats to land systems, especially regarding the supply of food, fibre and water (Daily et al., 2000; Dow and Downing, 1995; Folke et al., 2002; Kasperson et al., 1995; Raskin et al., 1996; Rosenzweig, 2003; Turner et al., 2003a, b). Studies of social learning and decision making have improved the understanding of how coupled socio-environmental systems are sustained and cope with forces of change (Cash et al., 2003; Kates et al., 2001; Lubchenco, 1998; Mooney, 2003; NRC, 1999; Raven, 2002). Additionally, advances in agent-based and other integrated modelling now permit these complex factors to be treated more systematically and holistically (e.g. Parker et al., 2001, 2003).

Land systems are complex, are driven by highly variable forcing functions (e.g. Berkes and Folke, 1998; Lambin et al., 2003; Lambin et al., 2001; Levin, 1998) and exhibit locally specific responses to the synergies between the human and environmental subsystems (Schellnhuber et al., 1997). All these factors emphasise the need for place-based analysis (e.g. by household, production, consumption and distribution unit, or ecosystem) to address vulnerability, resilience and sustainability (Cutter et al., 2000; Cutter, 2001; NRC, 1999; Wilbanks and Kates, 1999). At the same time, profound scalar dynamics in land systems (Parker et al., 2003; Schellnhuber and Wenzel, 1998; Steffen et al., 2004), and their diverse benefits to society require multiple spatio-temporal resolutions to be addressed in integrative analysis and assessment.

The three issues of Theme 3 identify the major advances in science required to meet the Theme's integrative and decision-relevant objectives. They address, in turn, (i) critical pathways of change in land systems, including ideas about the necessary progress in data and modelling integration; (ii) the coupled nature of the vulnerability and resilience of land systems and their relation to various hazards and disturbances; and (iii) the role of institutions in the sustainability of land systems.



Issue 3.1: What Are the Critical Pathways of Change in Land Systems?

Significant improvements have been made in understanding the dynamics of specific ecosystems, vegetation complexes and land uses. While refinement of this work is required, the importance of certain 'systemic' characteristics of land change dynamics has been revealed and warrants special attention (Schellnhuber et al., 1997; Holling, 2001; Steffen et al., 2004). The history experienced by land systems may shape future pathways of change (or their probability), bringing about a reconfiguration of land systems or their vulnerability and adaptive capacities, a process known as "historicity" or "path dependency". Land use dynamics are increasingly seen as spatio-temporal patterns that emerge from the interactions among system components (Lambin et al., 2003; Reynolds and Stafford Smith, 2002). In addition, the dynamics of land systems encounter thresholds that once crossed, shift the system into new states in non-linear ways. These characteristics of land systems appear to be pivotal given the pace, magnitude and novelty of land changes underway worldwide. It is fundamental to other Theme 3 issues to understand the critical factors, and the dynamics and pathways of land system change.

System Dynamics and Interactions Across Multiple Levels of Organisation

The interactions of the properties of various systems across multiple levels of organisation and scale are poorly understood for most land systems. Changes in biophysical or anthropogenic variables (like climate change or management practice changes) affect these interactions and in turn, often lead to emergent properties or coupled-system outcomes that could not be determined in advance. Changes in the fundamental character of a land system can trigger shifts to another state and hence function. In southern Yucatán, for example, repeated burning of sufficiently large parcels of land triggers an invasive fern. Once established, the fern impedes natural forest succession for lengthy periods, with implications for biota, biomass and nutrient cycles, and disrupts the usual slash-and-burn cycle of land use thus triggering the cutting of more forest (Turner et al., 2001). It is essential to improve our understanding of these system dynamics, as well as the thresholds and feedbacks in the development of complex adaptive systems.

When ecosystem structure or function is altered, the biogeochemical cycles and biophysical properties of the ecosystem are also likely to change, including the fluxes of carbon, nutrients, water and energy. Because of the importance of these fluxes in influencing regional and global atmospheric chemistry and climate, there will be significant feedbacks to the Earth System.

Long-term Perspectives on Land Change (Historicity)

The recognition of historicity (or path dependencies) operating in land systems is an outcome of system research and integrated modelling. Decisions made in the past constitute the initial conditions for our present-day landscapes. That is, past land system practices may 'lock out' future options, constraining the pathways that can be taken. For example, loss of biodiversity (especially keystone species) critically reduces the number of possible pathways for ecosystem change, including the chances for return to former structure and function. Brown-fields are a strong example of this at the urban-rural interface. The regulations surrounding the use of these lands contaminated by toxic wastes commonly inhibit their rehabilitation leading to their abandonment, and pushing urban land uses into less densely settled and open lands. In these cases urban areas lose their tax base as well as potential areas for urban occupation (e.g. Colten, 1994).

While brown-fields constitute an extreme case, conditions and contingencies of past land systems affect future land systems by a large range of factors. Most of these factors have not been well documented or incorporated into land modelling. Research needs to be structured in such a way that study designs include the search for path dependency and emergent properties as well as non-linear characteristics of change, adopting a very long-term perspective that covers past, present and future developments.

Models of Varying Degrees of Complexity

Many of the advances in Issue 3.1 will be generated by synthesis and comparative case study assessments which link expertise on the structure and function of land systems in different world regions with expertise on complex dynamic modelling. Models of varying degrees of complexity in space, time and process representations have been developed to test hypotheses of past, present and future behaviour against different data sets (Irwin and Geoghegan, 2001; Parker et al., 2003). The simpler models are easier to formulate, reduce the probability of human-induced errors, are computationally inexpensive, can be run through multiple sensitivity experiments, and produce results that are easier to analyse and understand. Indeed, the use of simpler models, with their level of abstraction, often enhances understanding of major system controls.

However, these simpler models often neglect important processes or scales at which real world phenomena act, requiring the use of more complex models. One of the major challenges is to incorporate second order dynamics of change (change of change over long time horizons) into such modelling, as well as incorporating feedbacks

Box 9. Biomass Enhancement

Increases in atmospheric carbon dioxide concentrations due to human activities may affect the growth of terrestrial plants – a possible negative feedback on atmospheric carbon dioxide. This feedback is being investigated in many ecosystems around the world, coordinated by IGBP in the international Terrestrial Ecosystem Responses to Atmospheric and Climatic Change (TERACC) network. Consistent patterns have emerged, including a linkage between water availability and ecosystem carbon dioxide responses, particularly in water-limited grasslands.

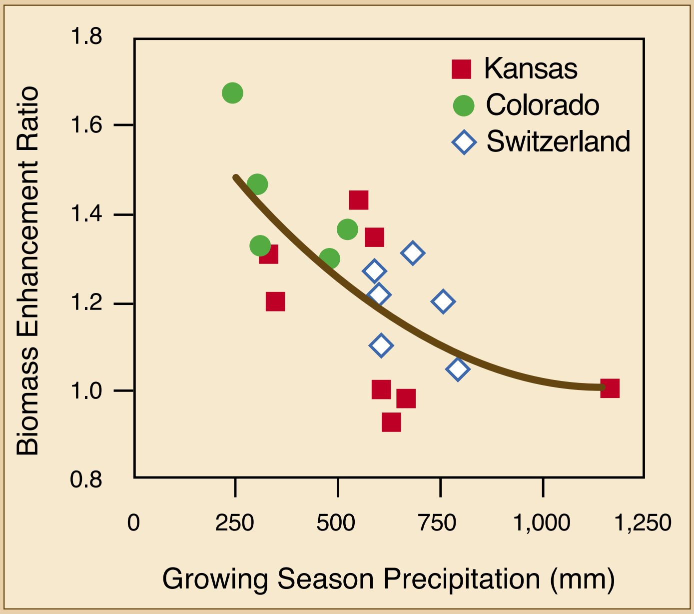


Figure 12. The enhancement in above-ground plant biomass from elevated carbon dioxide was greatest in dry years in three grassland experiments. From Morgan et al. (2004); reprinted with permission from Springer-Verlag.

The effects of elevated carbon dioxide on ecosystems are not constant over time, but vary in response to spatial and interannual variability in climate, such that global and regional changes in temperature, precipitation and other variables may enhance or offset the effects of elevated carbon dioxide. GLP will help to advance the understanding and quantification of these complex interactions.

within and across spatial and temporal scales. While the more complex models are better representations of actual system mechanics, their results are more difficult to understand, have the possibility of compounding errors that lead to unstable solutions, and are computationally expensive. A comprehensive understanding of the land system necessitates nested and linked models of varying degrees of complexity to address the same region or problem. Issues of uncertainty and error propagation should be a specific target of this research.

Much land system knowledge is predicated on semi-quantitative and qualitative information. Methods need to be developed to integrate such qualitative data into existing models and scenarios in such a way that the inherent uncertainty of qualitative data and knowledge is obvious to the modeller as well as the model user. Integrated models can be invaluable in the governance of land systems, and various scenario techniques and agent-based models can provide insights about the decision process itself (see *Implementation Considerations*). To ensure the policy-relevance of this work, the ultimate logic of these modelling activities needs to be directed towards the future. They need to deal with the unpredictability of land system changes by formulating outcomes in terms of alternatives, perceptions, choices, risks and opportunities.

Summary

- Improves the understanding of the dynamics of land systems, as well as the thresholds and feedbacks in the development of complex adaptive systems.

- Further develops and improves dynamic regional and global models of ecosystems to synthesise and test the understanding of the controls on feedbacks and the temporal and spatial patterns of feedbacks, and to project future trends in regional or global feedbacks from terrestrial systems.

- Designs research activities that adopt a very long-term perspective which covers past, present and future developments, to contribute to improved understanding of the historicity of land system change and the emergent properties and non-linear characteristics of these changes.

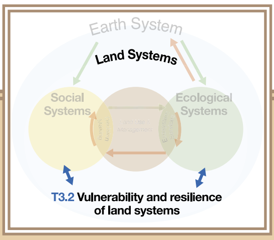
- Applies and promotes the improvement of models of varying degrees of complexity to integrate quantitative data sets with qualitative data on the structure and function of land systems in different world regions.

- Attempts to incorporate the second order dynamics of change into complex dynamic models as well as the feedbacks within and across spatial and temporal scales.

- Tries to achieve policy relevance by formulating outcomes in terms of alternatives, perceptions, choices, risks and opportunities.

Contributing Community

GCTE, AIMES, iLEAPS, MEA, LOICZ, GECHS, IDGEC, LUCC, PAGES, GCP, GWSP, GECAFS, Resilience Network, TERACC, BASIN, FluxNet, BATREX.



Issue 3.2: How Do the Vulnerability and Resilience of Land Systems to Hazards and Disturbances Vary in Response to Changes in Human-Environment Interactions?

Vulnerability and resilience research themes are gaining importance in several natural, social and application science fields (e.g. Kasperson and Kasperson, 2001; Turner et al., 2003a; Blaikie et al., 1994; Carpenter et al., 2001; Gunderson, 2000; Gunderson and Holling, 2002; Harrison, 1979). Emerging respectively from risk-hazard studies and ecology, vulnerability and resilience have been incorporated in frameworks applicable to land systems (e.g. Downing et al,. 2001; Kasperson and Kasperson, 2001; McCarthy et al., 2001; Turner et al., 2003a, b; Watson et al., 1997). These frameworks evaluate how hazards and disturbances and exposure to these, affect the sensitivity and resilience of the land system, including the consequences for the land system of resultant adjustments and adaptations.

Vulnerability-resilience assessment is central to GLP for at least two reasons. Firstly, land systems are exposed and respond (adjust, adapt or resist) to hazards and disturbances, the resulting mechanisms sustaining the systems or placing them at risk of change. Secondly, the identification of those components of the land system most at risk and the mechanisms that enhance risk mitigation are central societal concerns. Decision makers request information on both.

Metrics and Measures for Analysing Land System Vulnerability and Resilience

Recent work indicates that the concepts of vulnerability and resilience can be applied to land systems, including through the use of quantitative indicators (e.g. Adger et al., 2000; Luers et al., 2003). There are various recent or current attempts to develop metrics and measures relevant to the assessment of land system sustainability, and it is generally recognised that these tools and methods must be highly sensitive to place-based analysis, incorporate quantitative and qualitative data, and explore land system syndromes and complex indicators, integrated modelling and simulation techniques, and statistical downscaling (Turner et al., 2003a). Many researchers and practitioners have also begun developing metrics and measures of vulnerability and resilience. For the most part, however, these efforts address one or the other of the human and environmental components of land systems, but not the vulnerability and resilience found in their coupling. Hence, vulnerability assessments to date have largely focused on the consequences of one kind of hazard or disturbance on defined and separate human or environmental subsystems, but have missed the synergies that follow from the interactions of people with their environment.

An important element of analysing these interactions and of defining metrics is to understand the values, knowledge structures and preferences of various social actors in different societies, including policy makers. Development of a categorisation of the potential future conditions or states preferred by different community interests would be beneficial, so as to ensure that the considered metrics of sustainability inform and empower all protagonists equally in debates over future options.

Coping Capacities of Land Systems

Land systems commonly experience multiple hazards and disturbances, and the pace, sequencing and extent of them ultimately affect land systems and the mechanisms of adjustments and adaptation strategies that follow to compensate for the damages incurred (Turner, 2003b). Treating vulnerability and sustainability in this way is a relatively new research perspective and requires an improved understanding of how the types and properties of hazards and disturbances affect land systems and their coping capacities.

An equally fundamental issue is how the adjustments and adaptations of land systems and their coping capacities, alter their exposure to hazards and disturbances, and how changes in coping capacities affect the impacts experienced. For example, the large-scale engineering works erected along the lower Mississippi River to control 'normal' flooding, have reduced flood events on settlements and cultivated lands, changing the preparedness of these lands for the catastrophic floods of 1993 that overwhelmed the engineering works (Mathur and da Cunha, 2001).

It can be assumed that land systems the world over have incurred, or will incur, changes in their coping capacities due to global socio-economic transformations and global environmental change. No land system is closed to these external factors (Blaikie and Brookfield, 1987). The impacts of climate change on land systems drives home

Box 10. Vulnerability

Determining and examining linkages between vulnerability and resilience with reference to land systems across the varying perspectives of the participating sciences remains an exciting challenge.

The concept of vulnerability emerged from the social and application sciences dealing with risks and hazards. It considers the characteristics of individuals or groups in terms of their capacity to anticipate, cope with, resist and recover from the impacts of hazards (Blaikie et al., 1994). Resilience – the opposite of vulnerability – is used in the wider ecological community (e.g. Folke et al., 2002) to understand how ecosystem components are configured to enable it to rebound after perturbation. To date, natural systems are transparent in most vulnerability assessments, while ecosystem resilience focuses primarily on the biophysical processes in question.

The vulnerability and resilience of land systems are determined by complex interactions among ecosystems and a suite of political, economic and social conditions and processes. Not only do shocks or perturbations (e.g. war, conflict and climate change) and more constant stressors (e.g. economy, land use and nutrient cycling) affect the environmental and human components of the land system, but the consequences interact in ways that change vulnerability and resilience. The vulnerability and resilience of land systems must be studied in an integrated manner: a research challenge for GLP.

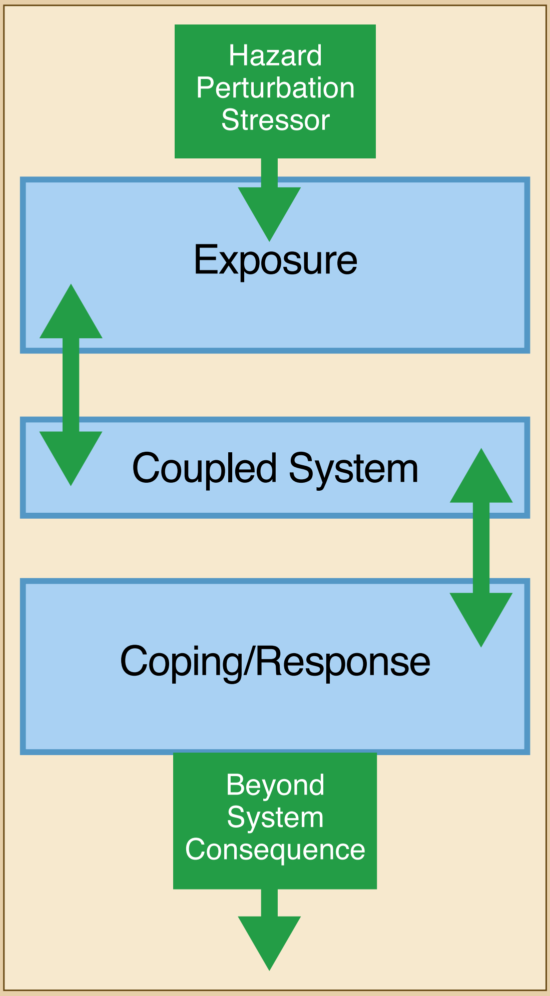


Figure 13. The linkages between perturbation and system response encapsulated in the concept of vulnerability.

this point for natural processes. However, the world-wide connectedness of economic activities increasingly requires an understanding of how land systems account for external human factors as well. The large-scale forest fires in Borneo in 1997, for example, followed from a constellation of factors, including international timber demands, ineffective controls on logging concessions and El Niño (Wooster and Strub, 2002). What are the factors and processes beyond land systems that affect their vulnerability and resilience, and how do the associated adjustments and adaptation in land systems affect those factors and processes?

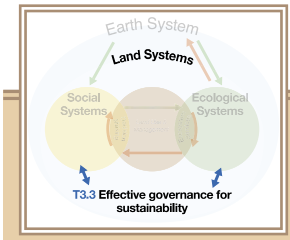
To analyse the vulnerability, resilience and adaptation of land systems in their coupling, a series of activities joining the different communities is required, including case studies designed specifically to address the vulnerability and resilience of the coupled land systems. They need to follow various recently developed holistic frameworks, as well as incorporate a comparative assessment of extant research. The scale of these types of research efforts needs to be expanded to deliver quality products, which must then be synthesised through modelling exercises (see Issue 3.1).

Summary

- Develops metrics and measures of vulnerability and resilience for the analysis land systems in their coupling.
- Analyses how the various types and properties of hazards and disturbances affect land systems and their coping capacities.
- Explores how changes in coping capacities affect the exposure to, and consequences of, hazards and disturbances.
- Assesses which factors and processes beyond a land system affect its vulnerability and resilience, and how the associated land system adjustment and adaptation affect these factors and processes.
- Develops case studies and designs to address the vulnerability and resilience of land systems in their coupling.
- Feeds back the results of these activities into complex dynamic modelling.

Contributing Community

People Land Management and Ecosystem Conservation, MEA, Resilience Network, iLEAPS, LOICZ, IHDP, GECHS, IDGEC, LUCC, Global Change SysTem for Analysis Research and Training (START), South East Asian Biosphere-Atmosphere Stable Isotope Network, GCP, GWSP, GECAFS, Global Energy and Water Cycle Experiment, GCTE, Resilience Network, International Centre for Tropical Agriculture, United Nations Environment Program, World Bank.



Issue 3.3: Which Institutions Enhance Decision Making and Governance for the Sustainability of Land Systems?

Institutions, clusters of rights, rules and decision making structures, play important roles in governing human interventions in land systems. Virtually no land remains 'open to access' on the part of users or is completely unaffected by institutions, although weak compliance mechanisms in some parts of the world lead to 'open access' outcomes resembling those referred to in the 'tragedy of the commons' (Hardin, 1968, 1998; Ostrom et al., 2002). Various situations also exist in which unsustainable land use practices are triggered by strong and well-enforced institutions, such as the recent, large-scale and out of control burning of forests in Indonesia (e.g. Jepsen et al., 2001; Vayda, 1999) and the demise of the Aral Sea (Kasperson et al., 1995). Detrimental impacts on land systems may also occur in places where multiple institutional arrangements, supported and enforced by different authorities (e.g. local managers, the state and NGOs) compete for control over the same resources or land, often with different uses or land cover outcomes in mind. Examples include local versus state control over woodlands in Rajasthan (Robbins, 1998) and the burning of savannah-woodlands in Mali and elsewhere in western Africa (Laris, 2002). A better understanding of the institutional dimensions of land use practices is essential for addressing the sensitivity, vulnerability and resilience of land systems.

The institutional dimensions and governance of land systems is precisely what provides a bridge to stakeholders and civil society. Policy of course, is linked to governance systems, and changes in international regimes, national, regional and local governance and NGO policies, affect land use practices with impacts on ecosystems, agriculture and water (Lambin et al., 2001). Policy shifts, for instance can: (i) affect the flow of migrants into sparsely populated lands, for example, the Brazilian Amazon (McCracken et al., 2002); (ii) open new lands for international operations, for example, Indonesian logging (Jepsen, 2001); (iii) change subsidies affecting the profitability of agriculture and the occurrence of land degradation (at least in the short-run), for example, livestock production in Karoo, South Africa (Archer, in press); or (iv) move subsistence cultivation into commercial cultivation, often with perverse outcomes, for example, expansion of pasture lands in south-eastern Mexico (Klepeis and Vance, 2003).

These examples illustrate the impact of institutions and associated policies on both the human and biophysical components of land systems. However, these aspects of land systems are less well understood and conceptually developed than, for example, those dealing with decision making by land managers. It is therefore important to address the consequences of the interactions among ecosystem services, land uses, institutions and polices for the maintenance of different land systems, including the roles of institutions in causing and confronting land system changes.

Institutions for the Long-term Maintenance of Land Systems

Different suites of institutions, governance and policies intersect with land systems in different ways, leading to different outcomes for the long-term maintenance of land systems. Research is only beginning to tackle these dynamics for different land systems, such as various use and enforcement practices in preserving biotic diversity within reserves (Bruner et al., 2001). A major lesson from the initial work is the need for local-state cooperation in the design of effective rules of governance and enforcement (Narayan-Parker, 1996). However, increasingly international accords affect land use and thus land systems worldwide, from agreements to keep almost all human activity out of Antarctica to carbon set-asides.

It is essential that Issue 3.3 identifies the institutional linkages from the international to the local scale. There are different levels of institutional connectivity between scales of governance or jurisdiction that influence decision making on land use under different levels of government representation or control. Institutional settings for the governance of, for example, land tenure, access to markets, or conservation of environmental properties, describe a complex suite of interactions, and there is a need to understand how national and international policies translate down to household activities as major drivers of land use decisions.

It is equally important to analyse the effectiveness and performance of international environmental and resource regimes aimed at land uses, for example, the International Tropical Timber Agreement. Some of these efforts have been effective while others have not, and the reasons for these differences need to be understood to guide the design of future institutions. Several projects, such IDGEC, address this issue in regard to specific resources (e.g. timber) or generic issues (e.g. loss of biodiversity) (Young et al., 1999). However, far less attention has been given to this linkage regarding land systems and specific sets of coupled socio-environmental systems (e.g. tropical forest biomes, xeric grasslands and irrigation systems).

Factors for Changes in the Governance of Land Systems

Changes in land systems feed back to institutions and the political economy, affecting their efficacy in management and governance. For example, a common property regime may be highly effective in maintaining grazing lands under sparse use, but not under intensive use. As intensity of use increases, changes in governance are required if the ecosystem services of the land system are to be maintained. The issue is more complex than the common-property–private-land ownership dichotomy, and often entails adjustments made internally within the land system rather than externally derived institutions. Research is needed to improve the understanding of the land system factors which interact to trigger fundamental changes in governance. This includes those sets of factors triggering endogenous institutional change, as well as the external factors enabling decision making, constraining options for land use activities, or determining coping and sustainability strategies. The effects of these factors also need to be linked to their emergent cross-scale implications.

Linking Institutional Development to Ecosystem Structure and Functioning

Most institutions do not govern land systems *per se*, but govern the use of specific goods and services in the system such as timber, water quality, food security or air quality. These goods and services have identifiable institutional constructs to monitor, with defined policy goals and a set of incentives or penalties. However, institutional agencies over many ecosystem services, such as nutrient cycling, soil formation or biological complexity, are poorly defined. Even if there are institutions associated with particular environmental components, the linkage back to ecosystem structure and function is not well formulated, and institutions are not necessarily constructed at the scale that is most appropriate to match the ecological processes. Research is required to understand how different institutions incorporate information regarding changes in ecosystem services into their framework, so that better governance can be attained.

The issues embedded in Issue 3.3 can be addressed through a series of syntheses and comparative studies, drawing on the range of research from common property networks to institutional theory. A synthesis activity needs to pull together the large array of this research to determine the insights gained for land systems, and to assess where there is a critical mass to answer major questions. Another effort requires linkages to IDGEC to address the question of international regimes and land systems, identifying and addressing those governance issues that directly and indirectly affect land systems. The products from these activities should be incorporated into modelling assessments.

Summary

- Seeks to understand the roles of institutions in causing and confronting land system changes.
- Assesses the effectiveness of institutions on different scales and seeks to understand the interplay between these institutions.
- Seeks to understand how policies at different levels translate down to household activities as major drivers of land use decisions.

- Draws lessons for effective future governance from the performance of institutions in managing land systems.

- Improves the understanding of the land system factors which interact to trigger fundamental changes in governance, including those sets of factors triggering endogenous institutional change, as well as external opportunities and constraints for institutional development.

- Seeks to understand how institutions associated with particular environmental components link back to ecosystem structure and function, and how this knowledge can be used for institutional development and sustainable governance of land systems.

Contributing Community

MEA, LOICZ, GECHS, IDGEC, LUCC, GCP, GWSP, GECAFS, Resilience Network, Common Property Network.

Implementation Considerations

GLP has a strong legacy on which to build, particularly the data sets, syntheses and research networks from GCTE and LUCC. However, closer integration of the complementary work of projects will be fundamental to GLP implementation. Coordinated or joint activities have been envisaged with other projects and programmes, including DIVERSITAS, IDGEC, GECHS, AIMES, PAGES, iLEAPS, LOICZ, GCP, GWSP and GECAFS. GLP and DIVERSITAS have established a strong partnership involving several components of Theme 1, because land use change and human perturbation of biogeochemical cycles have major impacts on biodiversity, and because changes in biodiversity will alter the functioning of terrestrial ecosystems. Both partners will collaborate on the elaboration of implementation plans and the establishment of networks that examine the relationships between biodiversity and terrestrial ecosystem function.

While development of a detailed and prioritised Implementation Strategy will be an early responsibility of the GLP Scientific Steering Committee, it is expected that GLP will be implemented through the synthesis of prior work as well as the collection and analysis of new data. Integration across disciplines and across scales will require the development of new analytical tools, and comparisons of land dynamics across regions will require major efforts in data compilation and dissemination. Working groups and networks of researchers will serve fundamental roles in the implementation of the project.

Case Studies, Manipulative Experiments and Integrated Regional Studies

In any given region, complex suites of social and environmental factors are operating simultaneously, and it will only be through broadly conceived research in targeted

Box 11. LBA: An Integrative Science Project

The Amazon Basin is the largest expanse of tropical rainforests and moist forests in the world, and is believed to embody around 25% of the world's biodiversity. Since 1970, the Basin has felt the impact of road-building, settlement schemes, mining and logging. Deforestation has rarely been less than 20,000 $km^2\ yr^{-1}$, and already more than 15% of the forest extent has been cut. These changes are expected to alter the cycles of water, energy, carbon and nutrients, and to affect local, regional and global climate. The Large-scale Biosphere-Atmosphere Experiment (LBA) is an international integrative science project (Nobre et al., 2002) involving 40 Brazilian institutions, 25 institutions in Brazil, Colombia, Ecuador or Peru, and many institutions in the U.S.A. and Europe.

LBA is guided by three key questions that integrate physical, chemical, biological and human sciences: (i) how does Amazonia currently function as a regional entity with respect to the cycles of water, energy, carbon, trace gases and nutrients?; (ii) how will changes in land use and climate affect the biological, chemical and physical functions of Amazonia, including sustainable regional development, and the influence of Amazonia on global climate?; and (iii) how do tropical forest conversion, regrowth and selective logging, influence carbon storage, nutrient dynamics, trace gas fluxes and the prospect for sustainable land use in Amazonia?

LBA is often referred to as a model for integrative regional studies because: (i) it was designed to integrate sciences across a range of scales using remote sensing, modelling, transects and site-specific studies; (ii) it uses a modular approach that allows research groups to work together while promoting interdisciplinary agendas; (iii) it has addressed not only scientific issues but also issues of concern to Brazilian policy makers; and (iv) it has advanced local education and training with several hundred masters and PhD students trained in less than a decade.

In LBA, emphasis is given to observations and analyses that increase knowledge of the physical climate, carbon storage and exchange, atmospheric chemistry, land surface hydrology and water chemistry, biogeochemistry, land use and land cover change, and human dimensions.

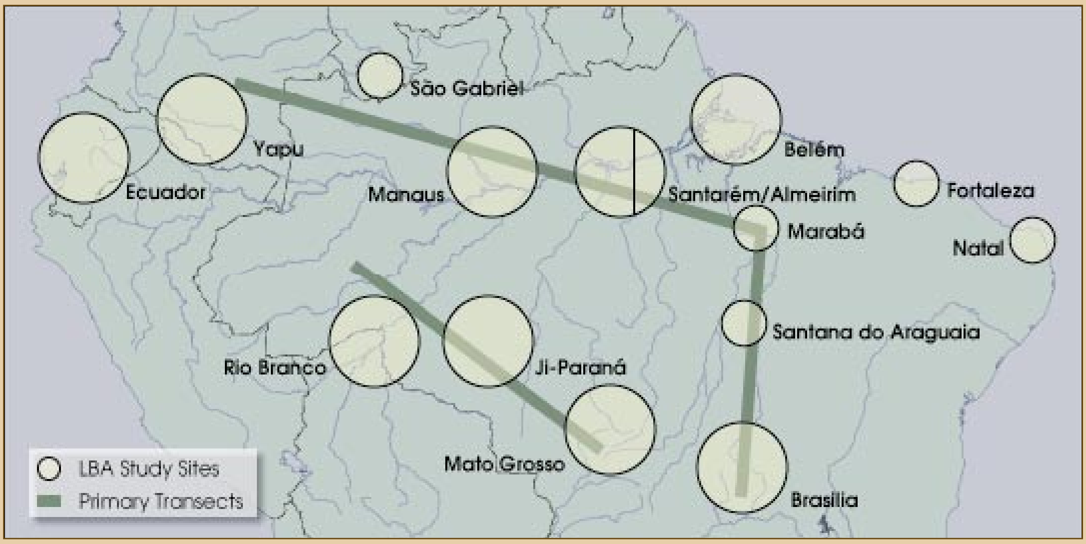


Figure 14. LBA sites span the Amazon from the headwaters in the Andes, along the Amazon and its tributaries to the mouth in coastal Brazil. Provided by the LBA science team and adapted by Robert Simmon.

In order to promote interdisciplinary and integrative science, research is organised around four science themes: (i) carbon dynamics; (ii) nutrient dynamics; (iii) trace gases; and (iv) land use and land cover change. Studies of carbon dynamics involve the quantification of carbon pools in vegetation and soils, and the rates of carbon exchange between the atmosphere, vegetation and soils, and the ways in which these rates are altered by natural and human disturbances. Studies of nutrient dynamics are focused on quantification of nutrient pools and fluxes and relationships with land use and sustainability. Trace gas and aerosol studies focus on the quantification of these fluxes and the identification of the biological and physical factors that control these fluxes, including the impact of human management. Land use and land cover studies focus on documenting past and current land use and land cover changes, developing the capability to predict the location and magnitude of future land cover changes in the region, and developing strategies that promote sustainability.

As LBA has evolved it has become increasingly clear that the human dimensions of the project had been underspecified, and that the questions posed did not adequately consider interactions between the physical and social dimensions and their feedbacks. GLP can contribute to projects like LBA by framing questions in ways that do not assume that either physical or social variables are solely determinant.

Additional information at wwww.lbaeco.org and earthobservatory.nasa.gov/Study/LBA.

regions that the multiple and interactive effects can be discerned. Integrated regional studies, along the lines of the Large Scale Biosphere-Atmosphere Experiment (LBA) in Amazonia, will play key roles in GLP research, integrating many biophysical and social dimensions of regional study sites. New integrated regional studies are currently being formulated, for example, focusing on Monsoon Asia, Northern Eurasia and West Africa, and may become important GLP implementation sites. There are however, unlikely to be sufficient integrated regional studies to cover all of the Earth's biomes.

Smaller-scale research efforts – process or case studies and manipulative experiments – will be needed to explore the linkages between ecosystem properties and services, and between ecosystem service delivery and societal structures. In general, the need to facilitate comparative analyses means they cannot simply be derived from existing literature, since questions and data will be incompatible. Rather, new synthesis work should be commissioned by teams of regional scientists agreeing to follow a minimum protocol. Case studies need to incorporate observations and measurements that allow for regional extrapolation and scaling.

Not all process or case studies need to be fully integrative or comprehensive in their measurements; however, they must address some critical linkages. Adopting principles based on biogeochemical budget closure or land system vulnerability will ensure more integrative case studies that consider interactions between subsystem elements. Case studies should be place-based, should establish interdisciplinary research teams, should be cognisant of the need to scale results up and down and across disciplines, and should explicitly define the relationship of the research to the broader coupled socio-environmental framework. Clear selection criteria for regional cases need to be developed and used from the outset. Since many of the participating disciplines might not be ready for cooperation in large groups, small sets of research groups could address integrative problems on the interface of natural and social sciences that require development of new methods and extraordinary data sets.

Once a set of standardised regional case studies is available, comparisons between regions can be undertaken. Several past efforts can guide this work, including intra-regional comparisons (e.g. Turner et al., 1993) and inter-continental comparisons (e.g. Tri-Academy Panel, 2001). Comparative analyses and synthesis will be two of the main research modes of GLP, and success will require careful and consistent definition of the variables of interest. Much work has focused on the simplest transitions, such as the conversion of mature forest to agricultural land. Intermediate forms of this simple case (e.g. forest degradation) are much more difficult to analyse, and other processes, such as desertification, are even more challenging. Meta-analyses must strive to overcome differences in protocols, for example, different techniques for manipulating temperature in plant growth experiments, or various definitions of human 'communities'.

Scaling within and across disciplines will be an important undertaking in GLP. Some phenomena are difficult to scale, especially those linking social activities to ecosystem services. In addition, certain phenomena are difficult to observe, and are therefore difficult to scale, such as soil and lateral water fluxes. It is necessary to determine how to represent spatial and temporal variability of the coupled socio-environmental system in terms of physical, chemical, biological and social structure and functions. The representation and modelling of the lateral exchanges between landscape components are important considerations in relation to changes in feedbacks and interactions between components of the coupled land system.

Initial Implementation Steps

GLP will take advantage of existing case studies: (i) of rural to urban land conversion; (ii) of arid lands that consider dryland problems in a comprehensive and integrative manner; (iii) of mountain ecosystems in different regions; (iv) of carbon cycle management; (v) of the impacts of global environmental change on agricultural land; and (vi) of freshwater ecosystems and their interactions will terrestrial ecosystems. GLP will link to case studies of rural to urban land conversion (along the urban-rural gradient) and consider the effects on ecosystem function and services. GLP will undertake comparative analyses of mountain ecosystem case studies in ecosystems threatened by systemic and human impacts. For carbon cycle management GLP will contribute by assessing the carbon sequestration potential of changes in land use, land cover and land management. GLP will also facilitate incorporation of case studies into the broader coupled socio-environmental framework by defining from the outset clear selection criteria for regional cases.

Integrated Analysis and Modelling

The three themes of this Science Plan have teased apart the land system to clarify the different components involved. However, a more complete understanding of complex land system dynamics (including the challenges outlined in the *Introduction*) will require better integration of component-level understanding.

Some of the most important advances in the understanding of the multiple dynamic interactions in complex land systems have come from computer models of these dynamics. For the next few years, GLP should put a significant effort into developing, and experimenting with, a wide range of models that integrate societal and natural dynamics. Models can be used to rigorously represent processes and ideas in ways that can be understood by practitioners from different disciplines using discipline-neutral terms; they can therefore help overcome misunderstandings that stem from different theories or assumptions. These attributes are particularly relevant in a domain based on reaching an understanding between the biophysical sciences, the social sciences and humanities. Modelling also helps formalise dynamical theories which can then be compared with observations, thus helping in process generalisations.

Modelling efforts to date have largely focused on the biophysical components of land systems. Advances are needed in the development of integrated decision making models, dynamic global land models, data-model fusion techniques and remote sensing applications. This will require integration of observation and experimentation methodologies. For instance, field studies of biogeochemical cycles, studies of below-ground biogeochemical processes and eddy flux tower modelling studies for terrestrial and freshwater ecosystems across all biomes will be needed to better quantify the effects of land use change, land cover change and other environmental changes on regional and global scale coupled biogeochemical cycles. This integration will provide new insights that help close biogeochemical budgets at various scales. Such studies need to incorporate the influences of human activities and other disturbances on biogeochemical cycling. Integration of remotely sensed data will enable extrapolation across regions and evaluation of spatial and temporal relationships.

Integrated research techniques are being developed based on advanced isotopic analyses, such as those used in BASIN. These techniques can assist in partitioning flux measurements into various components, such as photosynthesis, respiration and decomposition. Likewise, coupled estimates of trace gas fluxes (e.g. nitrous oxides, methane, volatile organic compounds and carbon monoxide) and the use of free-air-carbon-exchange experiments and ecosystem warming experiments will lead to a better understanding of integrated ecosystem responses to multiple stresses. The approaches of regional to global scaling are being enhanced through innovations in remote sensing and modelling. Dynamic global vegetation model (DGVM) development would benefit from a new round of model inter-comparisons to inform data-model fusion within and between disciplines.

Models must also be expanded to include socio-economic and socio-cultural components. The nature of socio-natural interactions and the dynamics of land systems are poorly understood, because most studies have focused on either social or natural dynamics. Model developments must focus not on simply the natural and human variables, but on different humanly constructed configurations of the relationship between the two, in which either natural or human aspects dominate. Understanding needs to move from studying human-environment interactions from the perspective of one domain or the other, to studying these two domains from the perspective of the interactions themselves.

Contemporary landscapes are the cumulative result of decisions made throughout the past, at least from when humans began altering landscapes around 10,000 years ago. Past decisions were taken in very different contexts, with different perspectives on nature, using different techniques and technologies, and with very different aims in mind. Hence, the very nature of the dynamics between societies and environments has changed through time, with important landscape impacts. Studying these changes over the very long term can help both understand the history of these changes and the present situation. A major challenge is to include second order dynamics of change (over long time horizons) in models, as well as the feedbacks within and across spatial and temporal scales.

Modelling land systems and their changes requires attention to: (i) processes operating at different spatial and temporal space-time scales; (ii) interactions between drivers, especially major policy shifts which often lead to emergent properties and non-linear outcomes; and (iii) spatially explicit outcomes which are affected by the scales of data generation and model application (Riebsame and Parton, 1994; Rajan and Shibasaki, 1997; Schulze, 2000).

Box 12. Dynamic Global Vegetation Models

One of the most significant advances in Earth System science of the last decade was the development of dynamic global vegetation models (DGVM), which incorporate land surface processes, ecosystem physiology and vegetation dynamics, and biogeochemical cycles within a single framework. These can be used to synthesise and test understanding of feedback controls and the spatial and temporal patterns of feedbacks.

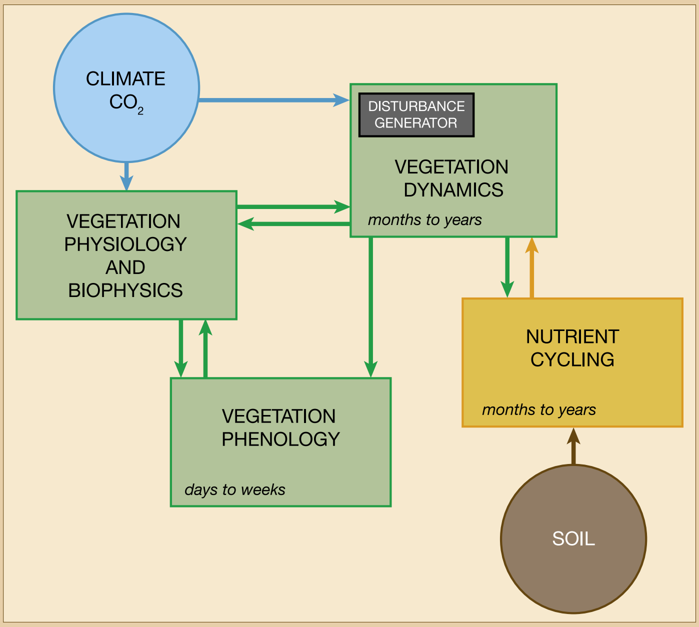


Figure 15. Modular structure of a generic DGVM with the time steps of the modules shown in italics. Adapted from Cramer et al. (2001) with permission from Blackwell Science Limited.

Further DGVM development is needed to: (i) improve representation of plant functional types; (ii) add animal functional types interacting with biogeochemical and biophysical process; (iii) improve representation of community development processes dealing with migration, dispersal and establishment; and (iv) improve representation of the control of vegetation productivity by grazers and pests. It should be possible to simulate the impact of changes in natural and agricultural grazing regimes using a limited number of animal functional types. Greater attention should be paid to landscape controls on the connectivity of landscape units affecting lateral fluxes of carbon, water, nutrients and sediments. Improved models are essential for projecting future trends in regional or global feedbacks from terrestrial systems.

Human interactions with vegetation play an important and increasing role in the dynamics of many landscapes, and in some cases, landscapes depend on regular disturbance by human beings. These interactions are not represented in DGVMs. Hence dynamic global land models must be developed that integrate the human and environmental sub-systems.

Controversies over the interpretation of palaeo and modern observations persist – an issue of importance for understanding the survival of natural ecosystems into the future. Hence more systematic studies are required that exploit the multiple examples of recolonisation of different environments found in palaeo-records. There is still considerable work required to determine what vectors lead to long-distance dispersal, and to characterise the major dispersal modes of individual plant functional types.

Representation of integrated biogeochemical cycling is not fully developed in many DGVMs. For example, estimates of sustainable sources and sinks of reactive nitrogen suggest that scenarios of future carbon storage by the land obtained using current DGVMs (e.g. Cramer et al., 2001) driven by rising atmospheric carbon dioxide concentrations may be unrealistic (Hungate et al., 2003). Improving the representation of nitrogen cycling within DGVMs, and in particular the controls on nitrogen fixation and leaching, is therefore a high priority task.

Social sciences tend to consider individual behaviour at the micro-level, examining decision making at the individual land manager level either by test or theory (Angelsen and Kaimowitz, 1999), or by multi-agent simulation and the search for emergent system properties (Parker et al., 2003). Considerations of individual behaviour seek ways to achieve spatially explicit outcomes, including at meso-scales of application (Irwin and Geoghegan, 2001), while multi-agent simulations can use decision rules in homogeneous contexts to move to the meso-scale for highly simplified landscapes. Various efforts are underway to improve both modelling approaches (e.g. Bura et al., 1996, Rouchier et al., 2001; Veldkamp and Lambin, 2001).

Natural sciences tend to focus on land at the macro-scale (Blöschl and Sivapalan, 1995; Peterson and Parker, 1998), often relying on empirical procedures that emphasise the spatial structure of land use, land cover and trends in land cover change to project the future (Veldkamp and Fresco, 1996; Verburg et al., 2002). This approach has recently been matched by the application of macro-economic theory to land systems using equilibrium models (Fischer and Sun, 2001).

Integration of land change science requires however, that modellers address a range of techniques and analytical issues, including data aggregation, metrics of outcome robustness and "real" feedbacks between social and natural processes (Kok and Veldkamp, 2001; Peterson and Parker, 1998; Pontius, 2000, 2002; Veldkamp and Fresco, 1997; Rajan and Shibasaki, 2000; Walsh and Crews-Meyer, 2002). These advances are critical to GLP, and the modelling community appears ready to address them.

Initial Implementation Steps

GLP must design a strategy for developing and experimenting with a wide range of models to integrate societal and natural dynamics. This strategy should include: (i) exploring methods to include semi-quantitative and qualitative information in existing models and scenarios; (ii) addressing the above a range of techniques and analytical issues to progress integration of social and natural factors at various scales in different modelling approaches; and (iii) progressing DGVMs toward dynamic global land models that integrate human and environmental sub-systems. GLP must also engage in IGBP and IHDP activities aimed at the epistemological, conceptual and methodological integration in the modelling of coupled socio-environmental systems.

Data Issues

Delivering on the GLP Science Plan will require better access to existing data, better knowledge of data quality and generation of new data in ways enable data sharing among researchers. The development of a freely available and continually updated spatially and temporally explicit database of land dynamics that reflects the frequency and intensity of extreme events, other disturbances and land use changes, will be needed to better evaluate current land conditions and project future land system changes.

Several critical global and regional data sets are required to evaluate the Earth System consequences of changes in ecosystem structure and function, and to test global land models. One obvious data set is spatially explicit historical climate data, which has recently been created at a very high resolution. Global land cover data are now becoming available through the use of satellite-based remote sensing. However, several important properties of ecosystems remain poorly known, including biomass, canopy heights, species distributions, disturbances and soil properties. Global databases containing high resolution data on key biophysical drivers of land change should be developed, including baseline data and rates of change for each variable. Many of these databases do not exist, so an important output will be the establishment of monitoring networks for atmospheric deposition, atmospheric composition, species diversity (e.g. the Global Observation Research Initiative in Alpine Environments) and water quality.

There is an urgent need for land use maps, especially at global and regional scales. Currently, most global mapping products are land cover classifications, with land use categories limited to cropland, pasture and urban. Land use information is needed to document the extent and intensity of anthropogenic activities on the land, including cropping systems, irrigation, fertilisation, crop yields and livestock density. Although available at the administrative level, such data are not always compatible between different countries, and are not always in a spatially explicit format suitable for ecosystem modelling. Data harmonisation and gridding are therefore often required. Also needed are regional and global data sets of population growth trends, institutional frames (economic and political decisions) and the history of ecosystem structure change (including human activities and disturbances such as fire) since contemporary land systems reflect a legacy of historical change. Some of the challenges involved include validating satellite data quality using ground-based observations, and assessing the spatial representativeness of field observations (normally point measurements) to enable up-scaling up to the regional or global level.

Data Assessment and Harmonisation

There is a need to characterise the current status of key data sets and to collate baseline data. Monitoring systems must extend beyond the existing climate monitoring system. Large quantities of surface data, including air and water quality, are being collected hourly and daily around the world, however, access to local data sets is difficult, and access to full continental data sets is challenging at best.

A coordinated effort is required to assemble the necessary data sets, evaluate data quality and document the data. Land cover and land use descriptions require standardisation. While a solid foundation has been laid for the standardised description of land cover by the United Nations Food and Agriculture Organisation, its Land Cover Classification System (LCCS) has yet to enter into widespread use. GLP must commit itself immediately to the adoption, improvement or replacement of LCCS, and to the development of an equivalent system for urban areas. Some initial efforts have been undertaken to standardise the description of land use, but additional and rapid progress on this front is required. This may entail an expansion of LCCS, the development of a parallel system, or a wholly new combined effort. In whichever case, it is crucial that GLP quickly plans and implements a standard approach to land use description.

Once the description of these crucial dependent variables is achieved, work can begin on the huge number of independent causal and contextual variables. While some work will be required on the handling of biophysical variables, it is the human and social variables that are especially problematic. The factors outlined in Issue 1.1 have been studied in various social sciences and the humanities, each using its own lexicon and methods of description, measurement and analysis. In order to understand how specific determinate structures enable and constrain options for particular land managers, it will be necessary to establish a rigorous system for the description and analysis of the contextual and causal factors associated with those changes.

The meta-analyses undertaken by GCTE and LUCC provide good starting points for developing a comprehensive catalogue of the crucial variables and the ways in which they have been treated in studies to date. The development of a standardised treatment of these variables must be carried out in close collaboration with partner research groups, especially DIVERSITAS and MEA, but also AIMES, PAGES and other IGBP, IHDP and ESSP projects. To achieve effective and ongoing meta-analyses, it will be important to build on existing networks and to develop networks, especially of regional scale analyses.

Box 13. Global Land Data Sets from Remote Sensing

Recent advances in satellite engineering, biophysical algorithms and automated data processing have allowed the regular production of new global data sets of essential land variables regularly for open scientific use. The Earth Observing System, initially launched in December 1999, has now completed the fifth year of continuous global land data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. The MODIS Land Team now produces an annual 1 km resolution map of global land cover with 3-month change detection, 0.5 km vegetation indices with a 16-day refresh interval, 1 km Leaf Area Index with an 8-day refresh interval, and daily 1 km gross primary production and annual net primary production. Details of these and other global land data sets are available at modis-land.gsfc.nasa.gov with actual data available on-line at edcdaac.usgs.gov/modis/dataproducts.asp.

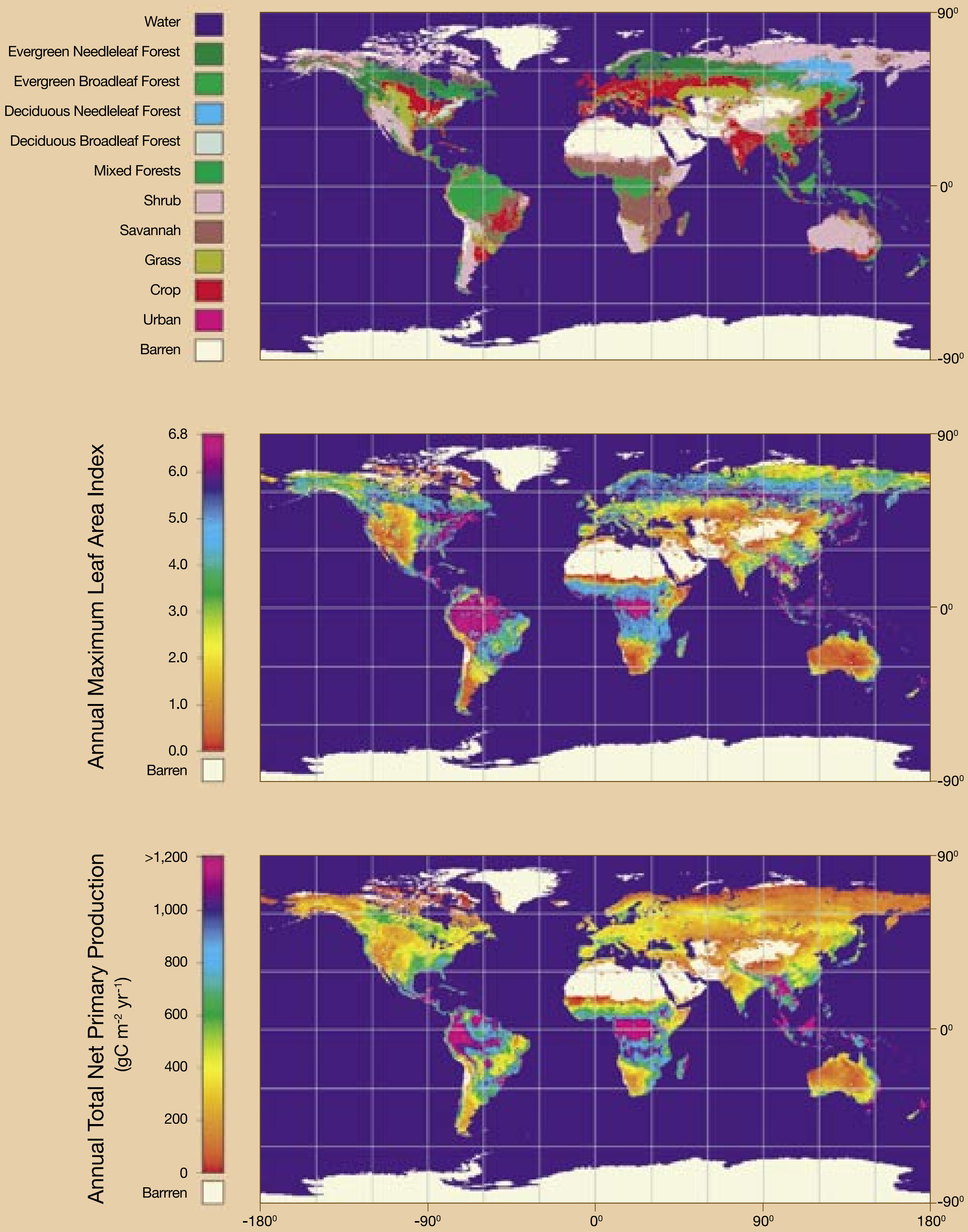


Figure 16. Global land cover (top), annual maximum Leaf Area Index (middle) and annual total Net Primary Production (bottom) data for 2003. From Running et al. (2004).

Data Sharing and Archival

Data sharing needs to be encouraged and data access needs to be improved. This is especially true for fine-resolution household and biophysical data collected in individual case studies. In order to facilitate data sharing within the GLP community, meta-data standards must be adopted. Data integration, especially at multiple spatial scales, will be a challenge. The spatial resolution of socio-economic data, remotely sensed images and ecosystem characteristics are often not compatible. In particular, there is a need for disaggregated socio-economic data beyond those data collected for specific case studies.

The secure archival of these data is a particular concern, and GLP should take advantage of existing archiving systems including the Global Terrestrial Observing System and the Global Observation of Land Cover

Box 14. FluxNet

FluxNet is a global network of micrometeorological towers that continuously measure carbon dioxide, water and energy fluxes between the land surface and the atmosphere (Baldocchi et al., 2001; Law et al., 2002). FluxNet was conceived by scientists from the IGBP project Biospheric Aspects of the Hydrologic Cycle and GCTE in the early 1990s, and now involves over 275 towers in 42 countries, generating nearly 400 scientific papers each year. Coordination and distribution of these worldwide datasets is at www.fluxnet.ornl.gov/fluxnet/index.cfm. FluxNet sites cover all major global biome types, and a full global range of bioclimatologies, with annual average temperatures from -13 to +26 °C and annual precipitation ranging from 100 to 3,000 mm yr^{-1}.

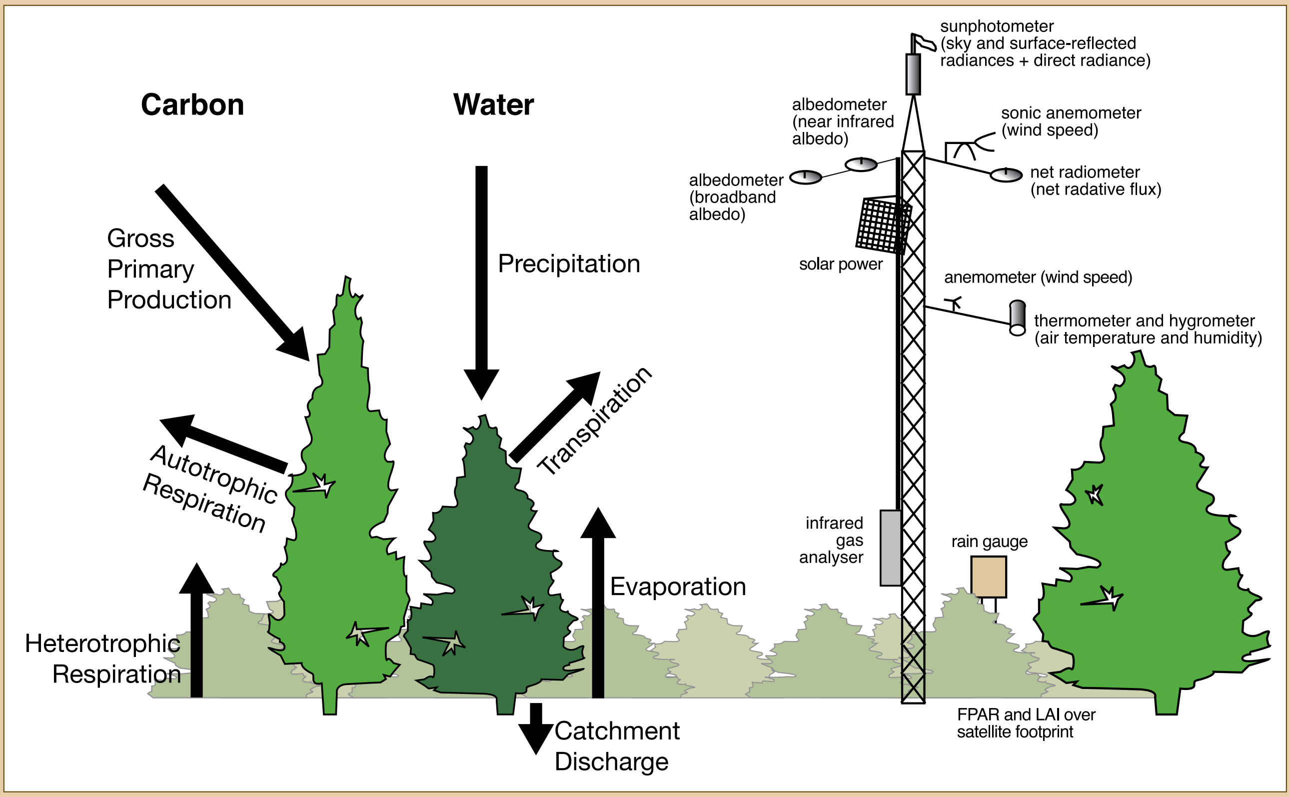


Figure 17. A generalised FluxNet tower configuration, showing instrument deployment and key carbon and water fluxes measured. FPAR is the Fraction-absorbed Photosynthetic Active Radiation and LAI is the Leaf Area Index. From Running et al. (1999); reprinted with permission from Elsevier.

project. Negotiating international data exchange policies is critical to the success of such an undertaking. Key data sets include land cover and land use, social and environmental data.

Initial Implementation Steps

- Develop meta-data standards for land applications.
- Move to adopt standard land cover classification systems.
- Develop common terminology and techniques for land cover classification.
- Expand data archiving efforts and link with existing data management systems.

Research Networks and Communication

To better focus GLP objectives and avoid duplication of effort, GLP should summarise in synthesis reports the current state-of-the-art in key areas. Networking with other groups working on similar issues – including social and physical scientists – will also be important. GLP will use networks, and networks of networks, including those formed by GCTE, LUCC, TERACC (the objective of which is to synthesise research on ecosystem responses and to improve communication between experimentalists and modellers), FluxNet (the goals of which are to understand the mechanisms controlling the exchanges of carbon dioxide, water vapour and energy across a spectrum of time and space scales) and BASIN (the aim of which is to improve the understanding of carbon cycle processes at the ecosystem, regional and global scales). Networks of scientists brought to bear on MEA should be recruited into the GLP to ensure coordination.

Development of new networks will be needed for emerging topics, such as the investigation of biogeochemical cycles in disturbed systems, case studies of urban impacts on the coupled socio-environmental system, or studies of agents of change for land use intensification. Where regional networks have been established and where assistance is needed in developing new regional networks, such as in Central Asia, joint activities will be developed with START. Joint activities related to research, training and the development of interdisciplinary research groups will be established in various regions where START has been active. The coordination of these efforts will broaden the research communities involved in GLP, and help the communication of research findings to scientists and decision makers in these regions. Further development will be needed to establish coordinated activities with START and other ESSP activities. These will promote regional interactions and better cross-disciplinary interactions.

Delivery systems – including websites, reports and workshops – that accelerate transfer of knowledge to all levels of society are important. An effort will be made to improve communication among researchers (both within and between disciplines) and between researchers and stakeholders. Additionally, existing research networks and linkages with existing mechanisms to transfer scientific results to the policy makers and decision makers (e.g. IPCC and MEA) will be strengthened. The GLP will also promote north-south equity, funding opportunities and capacity building.

Priority/Fast-Track/Joint Initiatives

Both GLP and DIVERSITAS are investigating the ways in which human systems respond to changes in ecosystem services, and how ecosystem services are related to ecosystem properties. As a result of this shared interest, GLP and DIVERSITAS will be developing a joint activity on ecosystem services, although DIVERSITAS will focus fairly narrowly on links between human systems and ecosystem properties as modified by changes in biodiversity.

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Appendices

Appendix I: Acronym List

AIMES	Global Analysis, Integration and Modelling
BASIN	Biosphere-Atmosphere Stable Isotope Network
BATREX	Biosphere-Atmosphere Trace Gas Exchange
DGVM	dynamic global vegetation model
DIVERSITAS	an international programme of biodiversity science
ENSO	El-Niño Southern Oscillation
ESSP	Earth System Science Partnership
EU	European Union
GCP	Global Carbon Project
GCTE	Global Change and Terrestrial Ecosystems
GECAFS	Global Environmental Change and Food Systems
GECHH	Global Environmental Change and Human Health
GECHS	Global Environmental Change and Human Security
GLP	Global Land Project
GWSP	Global Water System Project
IDGEC	Institutional Dimensions of Global Environmental Change
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
IPCC	Intergovernmental Panel on Climate Change
IPO	International Project Office
IT	Industrial Transformation (IHDP)
LBA	Large-scale Biosphere-Atmosphere Experiment in Amazonia
LCCS	Land Cover Classification System
LOICZ	Land-Ocean Interactions in the Coastal Zone
LUCC	Land-Use/Cover Change
MEA	Millennium Ecosystem Assessment
MODIS	Moderate Resolution Imaging Spectroradiometer
NEESPI	Northern Eurasian Ecosystem Science Project Initiative
NGO	non-governmental organisation
NSF	National Science Foundation (U.S.)
PAGES	Past Global Changes
SCOPE	Scientific Committee on Problems of the Environment
START	Global Change System for Analysis, Research and Training
TERACC	Terrestrial Ecosystem Responses to Atmospheric and Climate Change
WCRP	World Climate Research Programme

Appendix II: Glossary

Adaptation: a system response to perturbations or stress that is sufficiently fundamental to alter the system itself, sometimes shifting the system to a new state.

Adjustment: a system response to perturbations or stress that does not fundamentally alter the system itself. Adjustments are commonly – but not necessarily – short-term and involve relatively minor system modifications.

Biodiversity: the numbers of entities (genotypes, species, or ecosystems), the evenness of their distribution, and the differences in their functional traits and their interactions. The term encompasses a broad spectrum of biotic scales, from genetic variation within species to biome distribution on the planet.

Biophysical characteristics: land surface characteristics which affect land-atmosphere interactions. For example, properties related to albedo, surface roughness, fraction of vegetative ground, evapo-transpiration or biospheric water vapour exchange, and Leaf Area Index jointly contribute to define the biophysical state of a particular land surface.

Biogeochemical budget: stocks and fluxes of chemical constituents of the Earth System or its sub-systems.

Biogeochemical cycling: movement of key chemical constituents, such as carbon, nitrogen, oxygen and phosphorus through the Earth System or its sub-systems.

Decision making: unconscious or deliberate choices made on the basis of knowledge, perceptions and preferences. The range of choices available may be constrained by external factors.

Earth System: the Earth regarded as a unified system of interacting components, including geosphere (land), atmosphere (air), hydrosphere (water and ice), biosphere (life), and human activities and societies.

Ecosystem: a set of organisms (plants, animals, micro-organisms) and abiotic resources (e.g. nutrients and water) occurring and interacting within a given space, and characterised by the stocks (or pools) of elements, genes and energy and fluxes between them.

Ecosystem structure: composition of organisms present, their relative abundances, and their interactions (within and across trophic levels).

Ecosystem properties: sizes of compartments (e.g. pools of elements such as carbon, nitrogen and phosphorus) and rates of processes (fluxes of elements, compounds, material, organisms and energy among pools).

Ecosystem function: biogeochemical cycles (fluxes of elements) and other processes such as the dispersal of genes (e.g. via pollen) or organisms, and energy transfers.

Ecosystem services: benefits obtained from regulation of ecosystem processes, such as climate regulation, disease control, flood control and detoxification. Cultural and non-material benefits obtained from ecosystems include spiritual, recreational, aesthetic, educational, communal and symbolic services. Services that maintain or support conditions for life on earth include soil formation, nutrient cycling, pollination and biodiversity.

Environment: generically, the conditions in which a system or unit is embedded, either human, biophysical or both. Herein, environment refers to the abiotic factors of an ecosystem, including climatic, atmospheric and abiotic resource factors.

Exposure: the character of the hazard and the manner in which the exposure unit (e.g. ecosystem, agriculture, or coupled system) experiences the hazard.

Global environmental change: the set of biophysical transformation of states and flows of land, oceans and atmosphere, driven by an interwoven system of human and natural processes; these are intimately connected with processes of socio-economic and cultural globalisation.

Globalisation: the growing and accelerated interconnectedness of the world in an economic, political, social and cultural sense.

Hazard: threats to a system from stress or perturbation and the consequences produced.

Institutions: societal rules of governance that determine access and use of natural resources and environment. Land tenure, for example, is an institution governing land access.

Land cover: the observed (bio)physical cover on the Earth's surface, including wetlands, forests and grasslands.

Land management: the practices applied in the management of agricultural land (e.g. crop rotation, contour strip-cropping and fertiliser application) or forest land (clear cutting and selective logging).

Land system: an abbreviated term for the coupled socio-environmental terrestrial system that includes land use, land cover and ecosystems.

Land use: the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it, including parks, reserved, national-state forests, cultivation and settlement.

Perturbation: a disturbance to a system resulting from a sudden shock with a magnitude outside the normal vulnerability.

Resilience: the ability of a system to absorb perturbations or stresses without changes in its fundamental structure or function.

Risk: the conditional probability and magnitude of consequences following a hazard.

Sensitivity: the extent to which a system or its components is likely to experience harm, and the magnitude of that harm due to exposure to perturbations or stresses.

Stress: continuous or slowly increasing pressure (e.g. soil degradation) within the range of normal variability.

Sustainability: the development of systems capable of ensuring that future generations will have coupled human-environment systems capable of providing goods and services without degradation of structure or function.

Vulnerability: the degree to which a system, subsystem or system component is likely to experience harm due to exposure to a hazard. Herein involves not just exposure to a hazard, or a diminution in the provision of goods and services, but also the coupled system's sensitivity and resilience to multiple changes.

Well-being: includes basic material for a good life, freedom and choice, health, good social relations and security. The constituents of well-being, as experienced and perceived by people, are situation-dependent, reflecting local geography, culture and ecological circumstances.

GLP

The Global Land Project is a multidisciplinary project of the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP). Both IGBP and IHDP are interdisciplinary bodies of the International Council for Science (ICSU).

More information on the project sponsors can be obtained from:

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