12 August 2008

Ecosystem Change and Human Well-being –

Research and Monitoring Priorities Based on the Findings of the Millennium Ecosystem Assessment

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ICSU - The International Council for Science

Founded in 1931, the International Council for Science is a non-governmental organization representing a global membership that includes both national scientific bodies (113 National Members representing 133 countries) and International Scientific Unions (29 Members). The ICSU 'family' also includes more than 20 Interdisciplinary Bodies - international scientific networks established to address specific areas of investigation. Through this international network, ICSU coordinates interdisciplinary research to address major issues of relevance to both science and society. In addition, the Council actively advocates for freedom in the conduct of science, promotes equitable access to scientific data and information, and facilitates science education and capacity building. [http://www.icsu.org]

UNESCO

UNESCO was founded on 16 November 1945 with the aim to build peace through education, science and culture and communications. Today, UNESCO functions as a laboratory of ideas and a standard-setter to forge universal agreements on emerging ethical issues. The Organization also serves as a clearinghouse for the dissemination and sharing of information and knowledge, while helping Member States to build their human and institutional capacities in diverse fields. As of October 2007, UNESCO counted 193 Member States and six Associate Members.

Through its programmes and activities, UNESCO is actively pursuing the Millennium Development Goals, especially those aiming to: halve the proportion of people living in extreme poverty in developing countries by 2015; achieve universal primary education in all countries by 2015; eliminate gender disparity in primary and secondary education by 2005; help countries implement a national strategy for sustainable development by 2005 to reverse current trends in the loss of environmental resources by 2015. [http://www.unesco.org]

UNU

The UNU was established by the General Assembly on 6 December 1973 to be an international community of scholars engaged in research, advanced training, and the dissemination of knowledge related to the pressing global problems of human survival, development, and welfare. The UNU started activities in 1975 at its headquarters in Tokyo. Its activities focus mainly on peace and conflict resolution, development in a changing world, and science and technology in relation to human welfare. The University operates through a worldwide network of research and postgraduate training centres, with its planning and coordinating headquarters in Tokyo.[http://www.unu.edu/history].

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Report from an ICSU-UNESCO-UNU *Ad hoc* Group

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Preface

One of the recommendations from a Millennium Ecosystem Assessment (MA) Partners Meeting in Kuala Lumpur in September 2004 was that the International Council for Science (ICSU) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) should take the lead in addressing how the experiences from the MA could help identify needs for additional research that could fill some of the knowledge gaps identified by the Assessment. The United Nations University (UNU) later agreed to join ICSU and UNESCO in this follow-up activity and an *Ad hoc* Group was appointed by the sponsors in 2006 to carry out a scoping exercise to identify gaps in scientific understanding that impeded the MA.

There is a seamless link between research and assessments. The development of a science agenda should stimulate the science community to conduct additional research to address key issues in linking ecosystem services and human well-being. This is still a new area of research. The new research programme proposed in this report will provide opportunities for universities and other research establishments as well as funding agencies to structure their activities in such a way as to stimulate further research on the links between ecological and social systems.

The question of resilience of linked ecological-social systems was brought to the attention of the World Summit on Sustainable Development in 2002[1]. ICSU, speaking on behalf of the international science community at the Summit in Johannesburg, emphasized a few key points: (i) the science community must initiate research on the sustainable use of natural resources linking the environmental, social and economic dimensions, (ii) the agenda-setting must be done in a participatory fashion involving various stakeholders, (iii) the research much be place-based in order to address the integrated nature in a participatory fashion, (iv) and the science community must address the knowledge divide. At the initiative of UNU, UNESCO, ICSU and other partners signed the Ubuntu Declaration during the Summit with a pledge to capacity building in relation to science for sustainable development.

In addition, ICSU with partners published a report on Science, Technology and Innovation for Sustainable Development[2] as a follow-up to the World Summit on Sustainable Development.

There are several initiatives, such as the Earth System Science Partnership (the four global change research programmes of ICSU and others), the Resilience Alliance, and the Man and the Biosphere (MAB) programme of UNESCO, that already exist and

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[1] Folke, C., S. Carpenter, T. Elmqvist, L. Gundersen, C. S Holling, B. Walker, J. Bengtsson, F. Berkes, J. Colding, K. Danell, M. Falkenmark, L. Gordon, R. Kasperson, N. Kautsky, A. Kinzig, S. Levin, K-G. Mäler, F. Moberg, L. Ohlsson, P. Olsson, E. Ostrom, W. Reid, J. Rockström, H. Savenije and Uno Svedin (2002) Resilience and Sustainable Development. Science Background Paper commissioned by the Environmental Advisory Council of the Swedish Government in preparation for WSSD. ICSU Series on Science for Sustainable Development Vol. 3. ICSU, Paris, France.

[2] ICSU (2005). Harnessing Science, Technology and Innovation for Sustainable Development. A report from the ICSU-ISTS-TWAS Consortium ad hoc Advisory Group. Paris, International Council for Science.

contribute substantially in engaging the international science community. The development of a science agenda based on experiences from the MA should build on, and involve scientists from, the sub-global assessments that were an integral part of the MA. The initiative could also help stimulate the development of new sub-global assessments by engaging the science community in reflections over research needed to assess linked ecological-social systems.

The *Ad hoc* Group of experts with relevant natural and social science disciplinary competence representing experiences from the MA as well as the relevant sub-global assessments was convened with the following Terms of Reference:

1. Based on the outcomes of MA in general, and subsequent literature that has been developed[3], identify key knowledge gaps that should be filled through additional scientific research;
2. Prioritize research needs and indicate, whenever possible, the need for research at global *versus* regional scales;
3. Consider whether scientific progress will best be achieved through a decentralized bottom-up approach, regional foci through research/assessment projects, and/or an internationally coordinated research effort;
4. Suggest ways by which a research agenda could be further developed to address the identified priority knowledge gaps; and
5. Discuss and agree on possible mechanisms for implementing research to fill targeted knowledge gaps.

Funding was provided by allocating some of the money from the Zayed Prize that was awarded to the authors of the Millennium Ecosystem Assessment in 2006. Additional funds were provided by ICSU and UNESCO. The sponsors are very grateful to the members of the *Ad hoc* group that willingly offered their expertise and time. We hope that the report will stimulate many young scientists to embark on a journey to address the questions outlined in this report and thus help break the walls between the two cultures of natural and social sciences. We also hope that the report will stimulate funding agencies to support this exciting new area of research.

Under the leadership of the United Nations Environment Programme (UNEP) and the United Nations Development Programme (UNDP), we participate in a number of efforts to implement the findings of the Millennium Ecosystem Assessment. The follow-up strategy includes the following objectives:

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[3] Carpenter, S. R., R. DeFries, T. Dietz, H. A. Mooney, S. Polasky, W. V. Reid and R. J. Scholes. (2006). "Millennium Assessment: research needs." Science **314**: 257-258; Mooney, H. A., J. Agard, D. Capistrano, S. R. Carpenter, R. DeFries, S. Diaz, T. Dietz, A. K. Duraiappah, A. Oteng-Yeboah, H. M. Pereira, C. Perrings, W. V. Reid, J. Sarukhan, R. J. Scholes and Anne Whyte. Submitted. "Research for global stwradship: Building on the Millennium Ecosystem Assessment. PNAS (submitted)..

1. Build the Knowledge Base
2. Integrate the MA Ecosystem Service Approach into Decision-making at All Levels
3. Disseminate the MA through outreach programmes; and
4. Plan for Future Global Ecosystem Assessments.

This report constitutes a significant effort to address the first objective of the MA follow-up strategy. We hope that the research that this report and other publications will stimulate can provide a firm scientific basis for a possible second assessment of how ecosystem services contribute to, and depend on, human well-being.

Paris and Yokohama, March 2008

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1. Introduction

1.1. The Millennium Ecosystem Assessment (MA)

The Millennium Ecosystem Assessment (MA 2003, 2005 a-e) was a landmark effort for assessing the status of the Earth's natural resource base. It was innovative in design, comprehensive analytically and global in coverage. It evaluated the status of the foundation for ecosystem structure, biological diversity, how the Earth's ecosystems are functioning and their past, current and future capacity to deliver products, or services, to society. Finally it related ecosystem service delivery to human well-being, evaluated the capacity of current policies and institutions to meet the challenges of the current impairment of ecosystem functioning and service delivery capacity, and assessed various response options that could address threats to ecosystem services and improve the contributions of ecosystems to human well-being.

The results of this analysis were sobering. It found that some 60% of the services analyzed were degraded, with a particularly large impact over the past 50 years. Further, the scenarios for the future were not particularly encouraging since a continued degradation is projected unless a suite of new policies were put into effect that would reverse the tide of the destruction of the resource base that is crucial for future development without the continued degradation of ecosystem service delivery.

The analytical structure of the Millennium Ecosystem Assessment (MA) appears not only sound, but extraordinarily useful in revealing the linkages, compensations and tradeoffs between the activities of humans and the status of their natural resource base. Although the main features of this structure are relatively clear, the details for making the analysis in many areas of the assessment were sketchy. The required numbers, models and syntheses were not always there. This is due to many factors. As just one example, the science community has been extraordinarily active in accumulating information on the status of biodiversity and of ecosystems, stimulated in part by the Convention on Biological Diversity (CBD), but this information has not been related to how the condition of these metrics related to the delivery of services to society. As a consequence, the crucial linkage between ecosystem services and human well-being has not been a subject of study and hence information on this vital linkage, which is at the crux of the development-environment debate, has been missing

Thus, it became evident that there has to be a new effort to promote the kinds of knowledge that we need to better understand and hence respond to human-driven unfavourable trends in the trajectories of the Earth system. This report is prepared by some who were deeply involved in the MA, and who appreciate the analytical framework but were nonetheless frustrated by the lack of fundamental information that would have made the job easier and filled with less uncertainty in the projections. Here we look at the various knowledge areas that were encompassed in the MA showing where there were deficits in data, models and understanding. We do this with the conviction that the MA was a milestone that provides a baseline of where society is in relation to its utilization of the resource base that supports us all. We must follow this effort with subsequent assessments that will help us continually measure our progress toward a sustainable future. We call upon the research community to consider the priority needs expressed in this document so that we will be prepared to do the job in the future with a vastly improved set of analytical tools.

To stimulate additional research on coupled ecological and social systems using the MA conceptual framework, we call on the sponsors of this report (ICSU, UNESCO, UNU) to initiate detailed planning for a new coordinated research programme that will help fill some of the lacunas in scientific knowledge that we identified during the MA process and which are highlighted in this report.

We also call upon the policy and funding communities to continue to interact with and support this new programme of research. By focusing on the linkage between the status of ecosystems and the delivery of benefits, or services, to society the assessment process serves as a bridge between public needs and the science community through actions of policy makers working toward public good.

1.2 Conceptual framework

Multidisciplinary studies can fail because of different disciplinary cultures, languages, epistemologies and world-views among the contributors. An enterprise as ambitiously inclusive as an ecosystem assessment would be impossible to execute unless there was some level of agreement among the participants, and the authorizing environment and audience, about how to conceptualise the problem. Within the MA, the willingness to adopt a shared conceptual model was the single rule for participation. The degree of specificity versus abstraction of the conceptual model is a balancing act: too vague and general, and no convergence is possible; too much and legitimate alternate viewpoints are excluded. The MA conceptual framework took over a year to develop, through an iterative process, and was the first product of the Assessment – and a key outcome in its own right. Whereas in its most 'cartoon-like' form (Fig. 1) the conceptual framework is concise to the point of being simplistic, it was supported by a 250-page document with eight densely-argued, scholarly and peer-reviewed chapters by 61 authors, extensively referenced, and a glossary of hundreds of definitions (MA 2003). The interdisciplinary learning and intellectual comfort achieved among the thought-leaders of the assessment through the process of refining the conceptual framework was a key ingredient of the eventual success of the assessment.

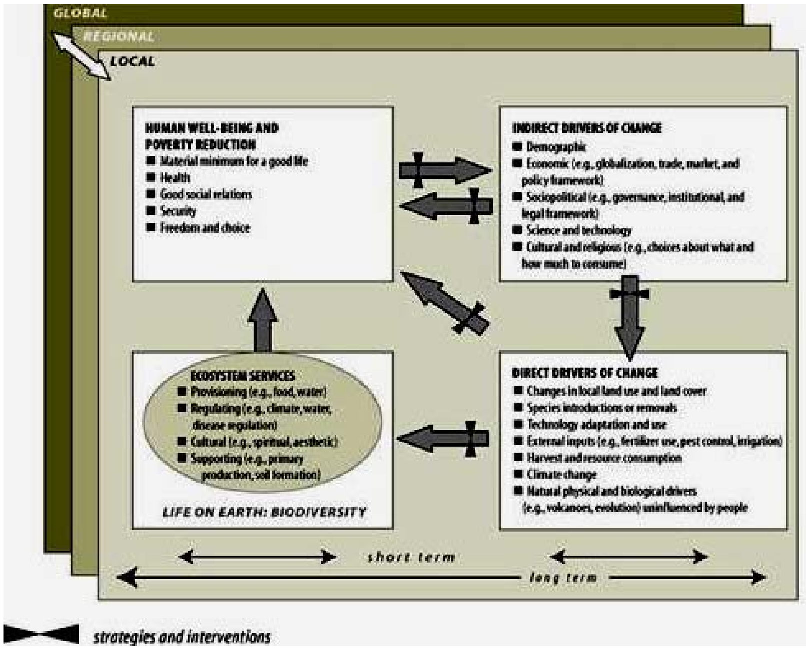

Figure 1. The conceptual framework of the Millennium Ecosystem Assessment (MA 2003).

Thus, future ecosystem assessments should build on the successful elements of the MA conceptual framework, but not simply adopt it unquestioningly. Importantly, the process of developing a shared conceptual model is necessary and should not be bypassed.

The successful elements of the MA framework were:

- The concept of ecosystem services as a way to build a connection between ecological and human systems;
- The typology of ecosystem services that was adopted (provisioning, regulating supporting and cultural services, each with about five subcategories);
- The embedding of the effect of ecosystem services on human well-being within a feedback loop that included both indirect drivers and direct drivers of ecosystem change; and
- The designation of ‘systems’ rather than ‘ecosystems’ as the primary units of analysis (see MA 2003, Box 3). This compromise avoided endless discussions about the boundaries and definition of ecosystems, helped to integrate human systems with ecological systems, and kept the resolution of the study appropriate. ‘Systems’ are mappable units delivering a predictable ‘package’ of ecosystem services. They are not biological units,

but combined ecological and human system constructs, taking into account not only biogeography and organism interactions, but also economic and political factors.

The less successful elements of the MA framework were:

- The relationship between biodiversity and ecosystem services was never sufficiently developed. As a result, establishing this link was only weakly achieved;
- The assumption that the MA conceptual framework was identical at all scales, and thus that the feedbacks always occur at the scale of analysis. In practice, biodiversity exists and ecosystem services are mostly delivered at local scales, whereas well-being is often expressed at local and regional scales. Similarly, direct drivers may be at local, regional or global scale and the indirect drivers are typically at regional to global scale. Cross-scale interactions are common;
- The failure to explicitly acknowledge that human well-being has determinants other than ecosystem services. Since these other determinants (for example, the income derived from 'manufactured capital' and 'social capital' rather than that derived from 'natural capital' (Dasgupta 2002) often overshadows the ecosystem effects; it was difficult to determine what part of the general rise in human well-being over the past two centuries was linked to ecosystem factors; and
- The relationship between regulating and supporting services and human well-being was poorly conceived, and this had consequences for attempts to value services. The regulating and supporting services are not directly consumed, and thus markets do not exist for them. They deliver their value through provisioning and cultural services.

The MA framework has been criticized for being utilitarian (*e.g.* McCauley 2006; but see also Reid 2006). A utilitarian viewpoint was an inevitable consequence of adoption of ecosystem services as the core concept. The MA adopted this position for pragmatic rather than ideological reasons, and makes no finding on intrinsic value. The people involved in the MA recognize the ethical issues associated with biodiversity loss, and in many instances are personally motivated by them, but did not try to include them in the same conceptual framework that was established for ecosystem services. They simply do not fit there, by definition.

2. Humans Influence Ecosystems and their Services

2.1 Elasticity, plasticity, time constraints, interactions among drivers and the implications for ecosystem service and human well-being

2.1.1. Direct and indirect drivers.

The MA distinguishes direct drivers, those changes that are most causally proximate to ecosystem changes, from indirect drivers, which shape the direct drivers and thus are one step removed in the causal chain (MA 2005c, Chapter 7). To date, the majority of research has focused on direct drivers, especially climate change, changes in biogeochemical cycles, changes in land use and cover and invasive species, including disease organisms. This is understandable because studying direct drivers is inherently simpler than including both indirect and direct drivers in an analysis and because research on direct drivers can be carried out within the scope of a single "meta-discipline", ecology. But future progress requires more attention to indirect drivers and a move toward approaches that link the social and ecological sciences. We must examine the full causal chain running from the indirect drivers through the direct drivers to ecosystem change.

There are well established structures of research in the social sciences that address the dynamics of key indirect drivers, including demographic change, consumption, production and globalization, socio-political institutions and culture and scientific and technological change. However, these disciplines have by and large ignored the link between their objects of study and ecosystems. Thus, we need to move from work in traditional disciplines in the social and ecological sciences toward the study of coupled human and natural systems, what might well be termed "human ecology". The intellectual rationale for this is clear—without a more integrative approach we are ignoring critical dynamics that drive the system.

There are practical reasons for understanding the influence of indirect drivers on ecosystem change. Our ability to intervene to mitigate adverse impacts and adapt to ongoing ecosystem changes usually involves shaping the indirect drivers. Thus, without understanding them, we have little ability to guide intelligently policy and other forms of decision making.

Bridging the current gap between the ecological and the social sciences is a substantial challenge. It will require new theory and methods and integrated data sets. Thoughtful efforts to develop an architecture for this more integrative work are in place (Richerson 1977; Moran 2006; Liu *et al.* 2007) However, progress will require sustained funding for this research, training the next generation of scholars and developing fora for sustained scientific discourse at the intersection of the social and ecological sciences.

2.1.2. Elasticity and plasticty

Effective intervention requires assessing both the elasticity and plasticity of the indirect drivers (York *et al*. 2002). The concept of elasticity is well developed in economics, where it is defined as the amount of change in a variable produced by a one unit change in a driver of that variable. Elasticity is an estimate of how much "leverage" one can gain by making changes in a particular driver. However, when thinking about how we might effect change we must also consider the "plasticity" of a driver—the ease with which reasonable actions and policies can induce change in the driver, and the time scale on which those changes will occur. The best "leverage points" for reducing adverse human impacts on ecosystems are those that have high plasticity and elasticity—we can change them and those changes have beneficial impact on ecosystems. For example, it is well known that the provision of family planning services, reduction in infant mortality and the empowerment of women reduce human fertility (Hirschman 1994). Those reductions slow the rate of population growth but the effect on population size works on a generational time scale. In contrast, changes in norms about consumption seem to sweep through populations quite quickly, on time scales of years or a decade. This would suggest that such changes might be a useful leverage point. But while a body of research on environmentally significant consumption is emerging it is not yet obvious how public policy could produce sustained and substantial changes in consumer norms (Stern *et al.* 1997; Dietz and Stern 2002).

Research on the elasticity of indirect drivers is still at a relatively early stage of development. However, there is a good bit of knowledge in the basic social sciences about the plasticity of some drivers, such as fertility, while for others, such as consumer choice and technological change, we know far less. What we do know about elasticity has not been organized to address issues of ecosystem change and effective response to it.

We also must acknowledge that the drivers interact. For example, the effects of changes in population size on the environment will depend on the level of per capita consumption in the population and on the technologies deployed to support that consumption (Dietz *et al*. 2007). This means that the effects of the drivers will be context dependent, varying from region to region, country to country and over time, and may be subject to non-linearities and threshold effects. This has strong implications for our research designs (Dietz *et al* in press). Most studies of direct drivers are conducted in one or a few relatively small study sites, with an expanse of a few hundreds or at most a few thousands kilometres. These studies have been and will continue to be valuable. But because they are localized, the variation in political and economic institutions and culture captured by a local study is of necessity limited. There are some important attempts to systematically compare local studies across regions of the world (Moran and Ostrom 2005) or within a nation (Sabatier *et al*. 2005). These efforts need expansion. In addition, the emerging literature that examines the effects of drivers at more aggregate levels, such as a region or a country are needed to complement the more micro-level studies.

3. Relationship between Changes in Human Well-being and Changes in Ecosystems

3.1. The relative influence of ecosystem change on human well-being versus other factors.

Although it was itself unable to say very much about value of the changes in ecosystem services it identifies, the MA has in fact changed the way that scientists are thinking about the value of ecosystems. By switching attention from ecological processes and functioning to the ecosystem services that contribute to human well-being, the MA has brought the analysis of ecosystem change into the domain of economics. Ecosystem services offer benefit streams that may be used to estimate the value of the underlying ecological assets. Moreover, those assets are not the traditional stocks of resource economics – minerals, water, timber and so on – but the systems that yield flows of such things.

The value of any asset lies in its role in attaining human goals, whether those goals are spiritual enlightenment, aesthetic pleasure or the production of some marketed commodity. It reflects the preferences of the many individuals in the economy, and is measured by their willingness to pay for the services that flow from the asset. This depends partly on the objective (*e.g*. physical or ecological) properties of the asset, but also on the socio-economic context in which valuation takes place – on human institutions, culture, the distribution of income and wealth, technology and so on. The value of ecosystems, like the value of any other asset, derives from the services they produce

A number of studies prior to the MA did address ecosystem services and the importance of quantifying the value of changes in ecosystem services in terrestrial (Daily *et al*. 1997), marine (Duarte 2000) and agroecosystems (Björklund *et al*. 1999), but the MA itself had great difficulty in attaching values to observed changes in ecosystem services in these systems. This is largely because of limitations in our understanding of the linkages between ecosystem functioning, ecosystem services and human well-being. A major item on the post-MA research agenda, therefore, is to enhance understanding of the linkages between ecosystem condition and functioning, ecosystem services, and the production of goods or services that contribute to human well-being. Ecosystems and the services they provide are, for the most part, intermediate inputs into the goods and services that enter final demand – that satisfy people's various desires. As with other intermediate inputs, their value derives from the value of those goods and services. To derive the value, however, it is important to be able to identify the marginal impact of a change in ecosystem components on the provision of the valued good or service. Part of the research agenda is to understand the degree to which ecosystem components can be substituted, and at what cost.

3.2. Understanding how changes in ecosystem functions affect those services and how changes in biodiversity affect those functions

Biodiversity [the number, abundance, composition, spatial distribution and interactions of genotypes, populations, species, functional types and traits, and landscape units] in a given system contributes to human well-being through its effects on the ecosystem processes that lie at the core of the Earth's vital life support systems. The MA provided the first comprehensive assessment of the ways in which supporting and regulating ecosystem services depend on ecosystem processes, and how these in turn are influenced by biodiversity. A first synthesis effort showed that different components of biodiversity (species richness, genetic richness, kind, abundance and range of functional traits) affect different ecosystem processes and services to different degrees (Díaz *et al.* 2006). For example, the number of plant and arthropod species seems to play a significant role in the regulation of agricultural pests and diseases, whereas the functional characteristics of the most dominant plant species appear considerably more important for a number of other supporting and regulation services, such as the preservation of soil fertility and water and climate regulation. Because of this, homogenization [the replacement of a large number of geographically restricted species by a small number of widespread species as dominants of communities] is a serious threat to the sustained provision of regulating and supporting services, probably more serious from a service perspective than the global extinction of already rare species.

The synthesis work of the MA showed that the number and strength of mechanistic connections between biodiversity and ecosystem processes and services clearly justify the protection of the biotic integrity of existing and restored ecosystems, and its inclusion in the design of managed ecosystems. It also points to the fact that it is functional composition (the identity, abundance and range of species traits) that appears to explain the main effects of biodiversity on many ecosystem services. However, there are a number of conceptual and empirical gaps to be filled:

Most of the evidence for the positive effect of species richness on biomass production comes from highly-controlled experiments conducted at a very fine scale (Naeem and Wright 2003). More studies are needed at the broader spatial and temporal scales that are relevant to land use management (typically hectares or km^2).

Information available corresponds primarily to fast-growing, short-lived herbaceous plants. More studies are needed on slower growing, woody plants and on other trophic levels. For example, increased plant biomass production at higher species richness observed in experimental mesocosms may not be directly relevant to carbon sequestration by forests at the landscape scale. A number of unknowns exist between these two extremes, such as the role of biodiversity in carbon loss as well as carbon gain, whether carbon storage increase monotonically with species richness or not, or whether the functional identity of the dominants is more important to carbon sequestration than the total number of species

Most of the information of positive effects of biodiversity on ecosystem processes is at the level of species richness (MA 2005b, Chapter 4; Balvanera *et al*. 2006). Very little is known about the role of diversity at finer or coarser levels. For example, genetic diversity is believed to play a crucial role in community resilience in the face of environmental change and variability, but the evidence comes mostly on the basis of theoretical work (Tilman *et al*. 1997, Yachi and Loreau 1999) and anecdotal evidence from the field of traditional agriculture. Recent experimental evidence has started to accumulate however (Zhu *et al*. 2000, Crutsinger *et al*. 2006, Schweitzer *et al*. 2005). There is very little work on the comparative roles of genetic *vs.* species richness in ecosystem processes and services. For example, it is not clear whether recommendations for highly managed ecosystems should give priority to one of these levels over the other in order to maximize the provision of certain ecosystem services (*e.g*. soil fertility, pest regulation). At the other end of the spatial scale spectrum, diversity at the coarse level of functional types and spatial distribution of landscape units appears to play a significant role in the regulation of climate via biophysical feedbacks (Chapin *et al*. 2000, Thompson *et al*. 2004). However, more precise information is needed on the most critical plant traits driving these processes. This information is crucial to refine global vegetation models of coupled interactions between land cover and climate.

Critical scales at which different components of biodiversity become important to ecosystem processes and services are not fully understood. Are there tipping points below which an ecosystem, however well-conserved, can no longer provide certain ecosystem services?

Finally, the most dramatic examples of effects of biodiversity changes on ecosystem services have involved alterations of food-web diversity through indirect interactions and trophic cascades. Most of these have been the unintended consequence of intentional or accidental removal or addition of certain predator, pathogen, herbivore, or plant species to ecosystems. These “ecological surprises” usually involve disproportionately large, unexpected, irreversible, and negative alterations of ecosystem processes and services. They usually involve novel interactions among species; they do not depend linearly on species number, or on well established links between the functional traits of the species in question and putative ecosystem processes or services. Because of these reasons, they are very difficult to predict using existing conceptual frameworks. Here the knowledge gap is not so much one of empirical data, since there are numerous examples (see MA 2005b, Table 11.2 for examples). Rather, there is a need to develop theoretical and methodological tools to deal with these intrinsically non-linear processes.

3.3. Theory and empirical research for estimating the values of ecosystem services

The MA drew attention – for the first time – to the value of services that regulate the capacity of ecosystems to continue to function over a range of environmental conditions. Given current concern over the environmental sustainability of development strategies, the regulating services are likely to be of increasing importance. Whereas the provisioning and, to a lesser extent, the cultural services are valued through market transactions, albeit imperfectly, the regulating services are not. Functioning insurance markets in some areas provide an indication of the value of specific regulating services, but these are typically few and far between.

The regulating services are thought to be connected to the insurance role of diversity (Loreau *et al*. 2002. ; Baumgartner 2007). Ecologists argue that an increase in species richness and the diversity of overlapping functional groups increases productivity and stability (Tilman *et al*. 2001) as well as resilience (Holling 1986, Folke *et al.* 2005). Stability has various interpretations, including fast return from perturbation, resistance to perturbation, or low variability over time (Ives and Carpenter 2007). Resilience also has multiple aspects, including (i) the amount of disturbance that the system can absorb and still remain within the same state or domain of attraction; (ii) the degree to which the system is capable of self-organization, versus the lack of organization, or organization forced by external factors, and (iii) the degree to which the system can build and increase the capacity for learning and adaptation (Carpenter *et al.* 2001). The proposed links among aspects of diversity and aspects of stability (or resilience) are supported by models and, in a few cases, experiments. It is important to note that only a few aspects of stability or resilience have been studied experimentally, and in some cases theories and experiments are mismatched so the tests are inconclusive (Ives and Carpenter 2007). A great deal of experimental work remains to be done to understand the connections of diversity and stability, or resilience, of ecosystem services.

A particular research challenge after the MA is to develop a deeper understanding of the role of diversity in the regulating services, and their impact on (a) the variance in supply of valued goods and services and (b) the severity of harmful events. In agroecological systems, a number of studies have analyzed the contribution of crop diversity to the mean and variance of agricultural yields and farm income (Smale *et al*. 1998, Schläpfer *et al*. 2002, Widawsky and Rozelle 1998; Di Falco and Perrings 2005). It would be possible to adopt similar analytical techniques to uncover the effect of changes in functional diversity on income in less heavily-impacted systems.

There is also scope to apply the expected damage function approach to estimate willingness to pay for the protection or enhancement of regulating services. Barbier's recent (2007) study of the effect of a change in wetland area on expected damages from coastal storm events is an example. This mimics the risk analysis applied in other areas such as drug safety (Olson 2004), and studies of the incidence of diseases and accident rates (Cameron and Trivedi 1998)

3.4 Tradeoffs: how changes in one ecosystem service affects others

There was a great enthusiasm for 'win-win' solutions in the early stages of the conservation-and-development debate (e.g. Rosenzweig 2003), but see also counter examples such as Roe *et al*. (2000). The unfortunate reality is that in an increasingly resource-constrained world, increases in one ecosystem service or human activity typically result in the reduction in other services or activities. A prominent finding of the MA was that the general increase in provisioning services over the past century has been achieved at the expense of decreases in supporting, regulating and cultural services, as well as biodiversity.

Making these tradeoffs explicit is a key function of ecosystem assessments. Trade-off analysis is the fundamental reason why the MA attempted, as far as possible, to quantify and determine the value of services. Economic analysis of tradeoffs employs the marginal value; the value of a unit increment or decrement of that service from its current supply. It is assumed that when trade-off decisions are made within a well-informed, relatively homogeneous decision-making community, where the loss of one benefit is balanced by the gain of another, the community can be relied on to make nuanced value-based judgments regarding such tradeoffs without technical interventions. But a large number of ecosystem service tradeoffs fail this test. The affected parties are neither homogeneous nor well-informed. In many cases, there is a spatial disconnect between the location where the benefits are derived and the costs are borne; for instance, better catchment management is a cost to highland people, but a benefit to downstream lowlanders. Increasingly, people live in cities, whereas the environmental services on which they depend (but are largely unaware of) are generated outside of cities, often far away. A special but critically-important case of trade-off asymmetry involves intergenerational inequities, where actions taken in the present result in a loss of ecosystem services in the future. The notion of a 'discount rate' is often used to address this trade-off, but many outcomes are critically-dependent on the precise value adopted for this discount rate, which is highly disputed. In the presence of system discontinuities that can be transgressed in the future, the entire notion of a discount rate may be untenable.

If two or more services can be accurately expressed in the same units of value – for instance, in economic terms – then making the trade-off decision is (at least conceptually) straightforward, and involves a simple cost-benefit calculation. Although the denominator of economic value need not be in monetary terms (for instance, for diseases and natural hazards it is often expressed in disability-adjusted life expectancies) it usually is expressed as a 'dollar value', because the tools for estimating and analyzing monetary values are well-developed and understood.

The experience of the MA was that such economic valuation was hard to achieve with consistency and confidence. In very many cases, the information needed to monetize the services does not yet exist. A useful contribution can nevertheless be made by describing (and where possible, quantifying) the causal chain by which value is delivered, without taking the analysis the final step to monetary value. Very many trade-off decisions are made without having all the factors in a common-denominator form, but those making the decision nevertheless need to have a feeling for the magnitude of the trade-off consequences. Even a narrative description of the pathway of impact is an advance over having no information at all. An important piece of qualitative information is the shape of the curves relating various levels of activity and the corresponding levels of delivery for key services. From these, it is often possible to agree that certain thresholds should not be exceeded (Scholes and von Maltitz 2007).

3.5. Costs, benefits and risks associated with the substitution of ecosystem services

Economic analysis of environmental resources has largely revolved around renewable and non-renewable resources. Within the class of renewable resources, focus has been on provisioning services like fish production, timber and other fibre products. The discussion on the regulating and cultural services has however received far less attention With the release of the MA report and improved understanding of the various ecosystem services and their inter-linkages, there comes a real need for the economic profession to improve its understanding of the economics of ecosystem services and how the various ecosystem services factor in economic production functions and the corresponding degree of substitution among them as well as with other factor inputs.

3.5.1. Strong and weak substitution of ecosystem services: Understanding their true values

One of the fundamental premises of economic production theory is substitution among factor inputs. Most economic production functions make an implicit assumption that inputs are substitutable. The degree of substitutability is often the main point of contention. The distinction between strong and weak substitution emerged during the 1970's and where the degree of substitution has varied from full substitution to zero substitution. The complexity of the problem rises ten-fold when we include regulating and cultural services in the equation. For example, the water purification and regulating service provided by a wetland is never considered in a typical production function for the supply of water. In most instances, these are intermediate services used in the production of final economic goods. Moreover, even if included in an economic production function, we are faced with the challenge that the service only starts to decline when some threshold is exceeded.

Thresholds determine to a large extent the scope for substitution among ecosystem services. The logical relationship would be the lower the threshold, the lower the degree of substitutability. But ecological thresholds are difficult to estimate and in most instances, safe minimum standards are recommended. However, this still begs the question on what these safe minimum standards (SMS) should be and how can these be factored in economic decisions. Although the concept of SMS is well discussed in the literature, empirical estimates for SMS are few and not well recognized in guiding policy making.

The level of substitution among ecosystem services also depends on the nature of the service under consideration. Some ecosystem services, in particular provisioning services, can be relatively easily assigned private property rights and the degree of substitution based on the relative prices of the services. However, there is a large class of ecosystem services, mostly regulating and cultural services, which are more difficult to assign property rights because of their public good characteristics. This difficulty translates to missing markets in these services and therefore their true values are never considered in economic decision making. There have been recent attempts to capture the values of these ecosystem services through the use of extended production functions

The MA stressed that one of the primary reasons ecosystem services were in decline was because their true values were not factored in economic decision making. Most decisions are based on market prices, but for many of ecosystem services no markets exist, and decision-makers have no clear signal as to the value of the services on which they rely. Their decisions have what are said to be external effects. Understanding the true social value of non-marketed ecosystem services depends on the way they are used by different stakeholders. There are a number of existing methodologies for estimating the value of specific non-marketed ecosystem services, yielding shadow or accounting prices for those services. But new methodologies need to be developed to derive the value of the ecosystem configurations that deliver different bundles of services (Barbier *et al.* in press).

An equal challenge is to find the appropriate institutional frameworks by which these public good ecosystem services can be managed as private goods through well defined property rights. Work done by Agrawal, Ostrom, Olson, and Chopra (Agrawal and Redford 2006, Chopra and Duraiappah 2008, Ostrom 2007, Olson 2000), among others, have offered insights into this problem but are still at an infancy stage and more work is needed to make an impact on policy decision making.

3.5.2. Social-distributive costs and benefits

The use of ecosystem services differs across stakeholders. This was highlighted by the MA. Use of one ecosystem service by a group of stakeholders may compromise the services available to other groups of stakeholders, forcing them to find substitutes. The costs of finding substitutes may be higher for one group versus another. The distribution of these costs needs to be known if public policy is to be used in designing mechanisms to 'internalize' the external effects of people's private decisions, or to assure the provision of ecosystems services that are important public goods, such as water provisioning, storm-buffering, habitat and so on. Knowledge of the benefits and costs accruing to stakeholders will also be useful in designing equity principles to guide the access, use and rights over ecosystem services (Perrings *et al.* in press). Baseline costs and benefits on the use of ecosystem services are rarely known and therefore difficult to evaluate if individuals have been left worse off or individuals have had an equal or equitable share of the net benefits. It is an area of research that borders between standard economic cost-benefit analysis and the political economy of moral imperatives and is currently lacking within the traditional disciplines of economics and social justice.

3.6. How is poverty affected by changes in ecosystems and their service

3.6.1. Introduction

In order to understand how poverty can be exacerbated or diminished through changes in ecosystems and their services, we need to have a deeper understanding on what constitutes human well-being and poverty and the type of indicators that will be needed to track changes in poverty due to changes in ecosystem services. The MA in its final analysis reported on the different intensities of the linkages between ecosystem services and well-being. However, the information and data used in making these conclusions were incomplete and based on expert knowledge and anecdotal information. Here we address the issues related to the strength of the causality between well-being constituents and ecosystem services and the degree of substitution across these links as well as the temporal, spatial and non-linear dynamics underlying trade-offs.

3.6.2. Understanding poverty

Human well-being and poverty are intrinsically linked on a continuum. The literature is rich (McGillivray and Clarke 2006, Sen 1997, Sen 1999, Dasgupta 2002, Alkire 2002, Narayan *et al*. 2000) with philosophical and pragmatic debates and discussions on the definition of well-being and poverty and the types of poverty that can occur. However, there is little information on how different definitions and perceptions of poverty can be affected by changes in ecosystem services. For example, income poverty will inadvertently focus on the material wealth that can be generated by ecosystem services and how this wealth can be used to reduce poverty. On the other hand if poverty is defined as more than being materially poor and includes security and health, then the emphasis can move from just looking at ecosystems as material resources to systems that can be managed in order to supply services that will contribute to these constituents of well-being. The relationships inadvertently change as the definition of poverty changes. The challenge is twofold. The first is to understand how well-being and poverty is framed and understanding how changes in ecosystem services affects well-being and poverty. The second challenge is to investigate how this understanding will affect the processes of making policy for poverty reduction.

The MA defined well-being as a context and situation dependent state comprising basic material for a good life, health, security, good social relations and the freedom of choice and action and poverty as the extreme deprivation of well-being. This definition embraced a multi-dimensional perspective of well-being with a number of constituents and determinants of well-being. However, the adoption of a multi-dimensional definition of well-being also introduced the complexity of finding indicators to represent well-being and poverty. A multi-dimensional approach will immediately bring to the fore discussion on weights and preferences. For example, the Human Development Index (HDI; UNDP 1990) takes into account three variables (life expectancy, literacy and GDP) and takes the simple approach by assigning equal weights. But this has come under increasing criticisms and there have been calls to revise the weighting structure. But assigning weights is a value-laden process and will need to represent the values of society in general. There are many methodologies available for determining values but recent advances (Smith 2007) hold considerable promise.

Comment [t1]: Not in ref. list

In addition to understanding preference weightings, there is the issue of defining the evaluative space for measuring well-being and poverty in such a multi-dimensional framework. In the MA, this evaluative space varied from using the constituents and determinants framework (Dasgupta 2002), the livelihoods framework (Chambers and Conway 1991), the material wealth or GNP that the Bretton Woods Institutions use (Summer 2006) and the Capability Framework (Sen 1985). There is no doubt a high degree of complimentary across all four frameworks, but there are subtle differences and the choice of the evaluative space plays a key role in policy decisions. For example, if we use income as the primary indicator for evaluating the success of poverty reduction strategies, then activities to increase the flow of provisioning services to increase income will be welcome. However, the negative impacts this increase in the flow of provisioning services will have on other services, like regulating and cultural services, may in turn cause a drop in the health and safety constituents of well-being but which are not considered when evaluating the success of the poverty reduction strategy.

However, irrespective of the evaluative space we choose for measuring changes in well-being, there will be at the minimum two different types of poverty to consider when trying to evaluate how changes in ecosystem services affect well-being. The first is absolute poverty and is based on some minimum threshold defined for well-being. The second type of poverty relates to relative poverty, which is the state of deprivation defined by social standards and is fixed by a contrast with others in society who are not considered poor. How changes in ecosystem services have an impact on these two different types of poverty is an area of work which is till uncharted. A cursory investigation of many of the poverty environment publications (primarily the World Bank, UNDP and DFID publications; see DFID *et al*. 2002 on the topic) show no acknowledgement of these different types of poverty and the appropriate policy responses that will be needed to reduce these different forms of poverty through ecosystem service management.

Once well-being and poverty types have been defined and indicators developed, the next step is to measure well-being and poverty. There have been some recent attempts (Shyamsundar 2002) to develop poverty-environment indicators, but most indicators still fall largely into two broad groups of poverty and environment indicators, respectively. A composite indicator having ecosystem services indicators as part of the composite index has yet to be developed. For example, the human development or human poverty index, which has ecosystem service indicators implicitly part of the composite index, would be a step in the right direction. For example, would including ecosystem services indicators to the HDI provide any valuable information for directing poverty reduction and development policies?

The other factor that has stirred a large debate in the poverty literature (Hicks 2006) is the aggregation issue. Most poverty indicators used today are based on aggregated data. This has the tendency to obscure pockets of poverty among socially disadvantaged and vulnerable groups. Henninger and Snel (2002) demonstrated how pockets of extreme poverty were masked by the use of aggregate data. Crude attempts to show the causality between these pockets of extreme poverty and ecosystem decline produced some interesting results, which could provide better at targeting the poor and appropriate ecosystem management policies to reduce the poverty. More research is needed to make this a part of targeted poverty reduction policies especially the Poverty Reduction Strategies and the Millennium Development Goals.

Thresholds have to be established so that poverty levels can be measured and tracked. In the case of monetary poverty, the indicator is the poverty line which is defined as the minimum amount required to purchase a person’s basic nutritional needs. The standard income threshold is a dollar a day which is then transformed to reflect the purchasing power in the respective countries. The threshold becomes much more complicated if the poverty indicator is multi-dimensional. This was never addressed in the MA and it presented a challenge for the respective chapter authors in the MA to make inferences on how poverty has changed as ecosystem services increased or declined.

Last but not least, is the establishment of benchmarks to evaluate progress of poverty reduction policies. Benchmarks are required to observe changes in the numbers of people who move in and out of poverty. The choice of a base year can have implications for end results. Benchmarks defined to evaluate just poverty may mask some important links to ecosystem changes. An appropriate base year as a benchmark, which is appropriate for evaluating against ecosystem changes has to be defined

3.6.3. Data availability and proxies

If income is used as the indicator for poverty, then which form of income will be used to measure poverty? Will it be gross income, net income, or disposable income and what are the implications of the choice on the final results? In the case when a multi-dimensional definition of poverty is adopted, then the choice of which data to use and the implication of different choice sets on final results becomes that much more complex. In the event information is not available, especially if constituents or capabilities are used as the appropriate space for measurement, then the issue of what proxy indicators can be used without losing the essence of the original proposed indicators emerges. This is especially true if the link with ecosystem changes is to be analyzed.

3.6.4. Understanding the links

In the MA, definitive conclusions were made on the strengths of the various links between ecosystem services and the constituents of well-being (Fig. 2).

Figure 2. The strength of linkages between ecosystem services and components of human well being. (MA 2005a)

The width of the arrow informs us of the intensity of the linkages between ecosystem services and the constituents of well-being. What factors influence the intensity of these links? The preliminary results from the MA identified culture, the weights assigned to the constituents of well-being and the degree of substitutability as some of the more critical factors influencing these links. However, the methodology used in determining the intensity of these links was based on expert knowledge drawing on the broad basket of results produced by the various working groups of the MA. This is a good start, but there is considerable scope for determining the intensity of these links using quantitative methodologies that will stand up to closer scrutiny and which will be accepted by policymakers.

3.6.5. Trade-offs and strategic behaviour

One of the main strengths of the MA conceptual framework was the inclusion of a clear analysis of trade-offs between ecosystem services as well as between constituents of well-being. However, what is missing in the analysis is a deeper understanding of what are the critical factors that underlie the decision to make trade-offs. For example, different stakeholders will have different levels of trade-offs they will have to make with respect to use of ecosystem services and the contribution to their well-being. Information at this level can help policymakers to design policies especially poverty reduction policies at targeted social groups

Understanding trade-offs at the individual and/or social groups' level is the first step. It will be equally important to understand how individuals or social groups interact with each other with respect to the access and use of ecosystem services. The degree of access and use of ecosystem services by individuals and/or social groups is strongly influenced by the institutional climate. The type of institutions and the organizations overseeing the efficient and equitable use of these institutions determine the access and use of ecosystem services. Work on informal institutions and the juxtaposition of formal and informal institutions is critical in understanding how ecosystem services are used in many developing and developed countries and will contribute especially in developing countries to more successful outcomes of poverty reduction strategies.

There have been many studies on how institutions mediate the access and use of natural resources. The picture on ecosystem services is a bit less well developed. Many ecosystem services, especially the regulating services, are public goods. The type of access, usage and ownership rights over these services is still at an infant stage. The move to create payments or markets for many of these services will have impacts across stakeholders and preliminary studies suggest that the socially excluded and vulnerable groups may see a drop in well-being and in some cases pushed into poverty with the adoption of these economic incentives. What supporting institutions are required in order to avoid these types of outcomes is an area of study needing urgent attention.

3.7. Coupling across space and time

The world has progressed far beyond the point where the interaction between ecosystem services and human well-being takes place exclusively at the local scale, or in the present time. The presence of processes ('tele-connections') that occur at large spatial scales – such as global trade patterns, or the global mixing of carbon dioxide in the atmosphere – means that actions at the local scale contribute to global or far removed consequences, and global, national and regional circumstances constrain the possibilities at local scale.

Similarly, the widespread occurrence of time lags, inertia and hysteresis in both ecological and social systems means that feedback loops do not automatically lead to optimal control – by the time impact signals are received, avoidance of the problem may no longer be possible. These complexities should be considered the norm rather than the exception. As a result, single-scale, single snapshot assessments are of limited utility, even if they are designed to be at the 'appropriate scale' – because there is unlikely to be a single appropriate scale. Multi-scale assessments that look backwards to the 'relevant past' and forward to the 'foreseeable future', and upwards for constraining factors and downwards for causes are much represent and ideal goal. Best of all are 'trans-scale' assessments that can handle the real-world situation, where system elements have characteristic scales, but are also coupled also across scales. This requires an iterative design that propagates information up and down the scale hierarchy. In order to avoid runaway complexity in such a scheme, a 'sparsely sampled, partially nested' hierarchy delivers nearly as much information as a fully nested, totally elaborated scheme. At a minimum, about three spatial scales are necessary – the global, the regional and the national, and in the order of 10 analysis units nested below each unit at the next higher scale are indicated. These rules of thumb are based on empirical findings from the multi-scale Southern Africa subglobal assessment (Biggs, et al., 2004).

4. Improving Capabilities of Predicting Consequences of Changes in Drivers

In the MA, a driver is any natural or human-caused process that causes a change in an ecosystem service (MA 2005c, Chapter 7; Nelson *et al*. 2006). An indirect driver affects ecosystems through a network of intermediate steps. Important indirect driving forces are demographic, economic, socio-political, cultural and religious, scientific and technological, and physical and biological. A particular indirect driver may affect many aspects of ecosystems through effects on many direct drivers, or factors which act expressly on ecosystems. Important direct drivers include land conversion, nutrient release, invasive species, harvest of living resources and disease.

In this section, we report key research needs to understand how drivers affect ecosystems and human well-being, and how those effects can be projected into the future. We address the need to improve capabilities for modelling connections of drivers to ecosystem services and human well-being, including the challenges of coupling different models. We also consider non-linear and abrupt changes which proved particularly challenging for the MA.

4.1. Modeling

The MA explicitly evaluated capabilities and shortcomings of existing models for forecasting ecosystem services in nine areas (land use and cover change, local and regional climate, food demand and supply, biodiversity and extinction, phosphorus cycling, nitrogen cycling, fish populations, coastal ecosystems, and human health) as well as integrated assessment modelling (MA 2005c, Chapter 4). We will not repeat that analysis here. Instead we will identify steps that could be taken within a few years to substantially improve capabilities of models for assessment of ecosystem services.

4.1.1. Consequences of changes in drivers on ecosystems and their services

Comprehensive assessments like the MA reveal important feedback pathways that are not addressed by existing models (MA 2005c, Chapters 4 and 9; Alcamo *et al*. 2005). For example, different models have been developed to address food supply and demand, land use change, interactions of regional climate with the land surface, and global carbon budgets. Each model is tailored to address key research or management questions in one topic area. A comprehensive assessment reveals that the topic areas are connected: food demand drives land use change, which affects carbon storage and land-atmosphere coupling, thereby altering the variability and reliability of food supply. Few of these feedbacks have been addressed by existing models.

We recommend that future model development address the most important feedbacks identified by MA that cannot be addressed by existing models. While all feedbacks involve multiple processes, land use and freshwater use are frequently involved in key feedbacks. Thus models of land-use change and freshwater dynamics may provide a backbone for expanded analyses of key feedbacks. Tradeoffs among ecosystem services (MA 2005c; Rodriquez *et al*. 2006) often lie at the nexus of key feedbacks. For example, decisions about ecosystem services often involve tradeoffs among agricultural production, freshwater quality and quantity, and biodiversity (Rodriquez *et al.* 2006). These tradeoffs suggest that feedbacks among food demand, land use, freshwater use, biodiversity and supply of food and freshwater need to be addressed by the next generation of models, as are considerations of important, but difficult to predict, technological innovations.

4.1.2. Consequences of ecosystem change for human well-being

While the MA was able to identify major trends in the physical magnitudes of a number of ecosystem services, it was unable to say much about the implications of these trends for human well-being. In particular, it was unable to say much about the impact of changes in ecosystem services on the value of the underlying ecosystems – the natural capital stocks. One reason for this is that despite the considerable effort that has gone into the estimation of willingness to pay for particular provisioning and cultural (often recreational) services, comparatively little effort has gone into the identification of the role of ecosystem stocks in underpinning those provisioning services. A major research challenge following the MA is to model the relationships among ecosystem function, biodiversity and services needed both to derive the value of ecosystem stocks and to predict the consequences of changes in those stocks.

Among the least-studied but most important relations are those between the ecosystem stocks and the risks associated with provisioning and cultural services. The mechanisms that regulate the impact of stresses and shocks on provisioning and cultural services are the basis for the so-called regulating services (Perrings 2006, Dirzo and Raven 2003). These include the impact of ecosystems on the establishment and spread of introduced pests and pathogens, including emergent zoonotic diseases like the ebola virus, HIV, SARS or avian flu (Dazak *et al*. 2000; Kilpatrick *et al*. 2006). The regulating ecosystem services determine the capacity of ecosystems both to regulate the impact of these shocks, and to respond to changes in environmental conditions without losing functionality (Kinzig *et al*. 2006). Although some effort has been given to the estimation of the expected damages associated with, *e.g.*, reduction in mangroves (Barbier 2007) this is a dimension of environmental sustainability that has been largely ignored by economists. The regulating services are, however, important wherever there is a distribution of outcomes, and wherever decision-makers care about the properties of that distribution. Hence they are more important, the more risk-averse are decision-makers. The regulating services typically depend on the functional diversity within ecosystems. Like asset portfolios in market economies, functional diversity in ecosystems moderates the risks associated with a given range of environmental conditions. Understanding and valuing the regulating services is a major research challenge.

The valuation of non-marketed provisioning, cultural and regulating services makes it possible to identify the social opportunity cost of ecosystem change. This in turn makes it possible to design instruments (payments for ecosystem services, prices, taxes, access charges, property rights, standards and so on) for the efficient allocation of those assets. Beyond this, valuation also provides a means of testing the environmental sustainability of anthropogenic activity. The MA recorded trends in the physical properties of a number of systems, but was unable to record trends in the value of those systems. This is largely because the work has not yet been done to support such an analysis. The adjusted net savings estimates produced by the World Bank[4] are an important step in the right direction in that they are designed to show whether the value of natural capital stocks is decreasing over time. The adjusted net savings measures currently used are, however, limited to traditional natural resource stocks, and these correlate poorly to ecosystems. Like periodic ecosystem assessments, periodic assessments of changes in the value of ecosystem stocks are central to an understanding of the environmental sustainability of economic development. We recommend that subsequent assessments include efforts to track changes not just in the physical magnitude of ecosystem stocks, but also in their value. This might be linked to the further development of the World Bank's adjusted net savings measures.

4.1.3. Coupling models of drivers, multiple ecosystem services and human well-being

Most existing models of ecosystem services were developed to address particular sectors (*e.g.* agriculture, fisheries, land use, water supply) or particular intersections of issues (*e.g.* biodiversity and land-use change). Moreover, these focused models must be coupled with projections of climate, demography, macroeconomic development and other drivers in order to assess or project ecosystem services. Coupling disparate models was a substantial challenge for the MA (Alcamo *et al*. 2005; MA 2005c, Chapter 9). For the MA scenarios (MA 2005c), models were coupled qualitatively through incorporation in the storylines (MA 2005c, Chapter 8; Carpenter *et al*. 2006; Cork *et al*. 2006) or soft-linked by sequentially passing output from one model to another (MA 2005c, Chapters 6 and 9; Alcamo *et al*. 2005). It would be preferable to have fully interactive models linked across sectors.

[4] http://go.worldbank.org/3AWKN2ZOY0

Qualitative and quantitative analyses are complementary. Each form of analysis makes unique contributions and must be integrated through the scenario process (Alcamo 2001; Carpenter *et al*. 2006). In most cases, integration is accomplished by iteration; qualitative storylines are developed, a quantitative analysis is conducted, qualitative analyses are revised in light of the model results, the models are revised and updated based on the new qualitative analyses, and so forth. In the MA, there was time for only one formal cycle from qualitative to quantitative, although some steps toward a second cycle took place at the regular meetings of the Scenarios Working Group. Although the team would have preferred more cycles, there was not enough time available.

Further work is needed to improve the coupling of qualitative and quantitative scenarios, and the integration of sectoral models, for ecosystem services and human well-being. Progress in these areas would substantially strengthen the foundation for future assessments of ecosystem services at national or global scales. Future assessments will be conducted in compressed intervals of time, and the assessment team will naturally focus on the task of organizing information in relevant ways to address the questions of the stakeholders. When an assessment is underway, there will not be time to improve the foundations of cross-sectoral modelling and integration of qualitative and quantitative information. These foundations should be improved before the next major assessment is undertaken.

4.1.4. Uncertainty, model transparency and uses of models

In most cases, the MA addressed uncertainty by stating the degree of scientific consensus and the team's degree of confidence on a particular point. However, in most cases uncertainty could not be quantitatively estimated by the MA. Research should expand and improve the capacity for measuring the uncertainty of statements about ecosystem services. For status and trends assessment, the research community should strive to quantify uncertainties as rigorously as possible. Often this can be accomplished by reanalysis of existing data. For scenarios and projections of regional or global dynamics, uncertainty analysis is much more difficult. Nevertheless some useful measures of uncertainty can be computed and the research community should attempt to address these

There is a cognitive gap between the technical and decision communities, and this gap is especially wide for rapidly evolving fields such as ecosystem services and human well-being. Investments to improve communication will substantially increase the value of assessments by prompting more relevant analyses and organizing results in more accessible and transparent forms. Considerable work is needed on topics such as how to ask questions that are relevant to stakeholders; communicating complexity and uncertainty to non-specialists; eliciting knowledge from stakeholders; integrating qualitative and quantitative knowledge; and understanding the coupling between model results and social or political processes (MA 2005c, Chapter 4).

4.2. Non-linear and abrupt changes

A recurring theme of the MA was "the absence of theories and models that anticipate thresholds, which once passed yield fundamental system changes or even collapse" (MA 2005c, Chapter 4). Some important ecosystem services subject to nonlinear changes include dryland agriculture, fisheries, and freshwater quality (MA 2005c). Once degraded, these services may recover slowly or not at all. Slow recovery and irreversibility translate into long-term losses of ecosystem services and persistent problems for managers aiming to sustain human well-being. Social systems are also subject to nonlinearities (Repetto 2006) and the interactions of social and ecological thresholds have scarcely been explored (Walker and Meyers 2004; Walker and Salt 2006).

4.2.1. Thresholds, leading indicators, and reversibility

In some cases, thresholds are known to exist but we do not know the combinations of drivers that will push the ecosystem across the threshold. Examples include loss of rangelands due to encroachment of woody vegetation (Walker 1993), economic decline of fisheries (Walters and Martell 2004), and degradation of freshwater quality (Carpenter 2003). These are repeated events (many breakdowns of rangelands, fisheries and water quality have been observed). Data could be synthesized to estimate how changes in drivers affect risk of crossing thresholds. In addition, leading indicators based on increasing variance, reddening of power spectra, or slowing of return times from perturbation may exist for the most important nonlinear transitions in ecosystems (Carpenter and Brock 2006; Kleinen *et al*. 2003; van Nes and Scheffer 2007).

In regional management, there may be multiple thresholds, some of which are completely unknown (Walker and Salt 2006). In these cases, methods based on careful monitoring, localized experiments, spreading risk, and other tools of resilience management become necessary (see below). Leading indicators may help (Brock and Carpenter 2006).

We can improve our capacity to assess thresholds that affect ecosystem services through three kinds of research: (1) Quantitative data for known thresholds should be synthesized in the open literature, to enable quantitative, data-based assessments of risk in relation to changes in key drivers; (2) Leading indicators of thresholds should be investigated experimentally under field conditions in large complex systems, *i.e.* at the scales of management; and (3) Methods of resilience management should be expanded, applied and assessed in practice (Walker and Salt 2006).

4.2.2. Implications of slow recovery and irreversibility for equity among generations; discounting

As with the problem of climate change, ecosystem change involves processes that operate over very different time-scales, small fast processes generally being embedded in large slow processes. This has a number of implications both for the way that processes are modelled, and for the way that decision-makers seek to learn from experience. Adaptive management of social-ecological systems (learning by doing) implies some form of Bayesian updating of models, but if Bayesian updating is driven only by movements in the fast variables of the system, and ignores the slow variables, it can lead to misleading predictions of system behaviour and hence inappropriate management responses (Brock and Carpenter 2007). Managers can learn the wrong things. The first research challenge is therefore to develop a deeper understanding of the dynamics of anthropogenic ecosystem change, and especially for the slower variables. This is a prerequisite both for the development of better predictive models and for improved adaptive management.

Long-term ecosystem change, particularly if irreversible or only slowly reversible, necessarily affects future generations. Aside from the question of how best to model such long-term processes, this raises the issue of how to account for their effect on the well-being of future generations. The two concerns here are how to model the responses of decision-makers to observed changes in the system over time, and how to weight the well-being of future generations (*i.e.* what discount rate to apply). It is clear that our capacity to model technological and other responses to observed ecosystem change is limited. Indeed, this is partly what lies behind the heavy use made of scenarios in the MA. But there is scope for doing very much better than in the past. Most economic assessments of the long-term impacts of climate change, for example, turn out to be highly sensitive to the assumptions made both about the balance between both mitigation and adaptation in human responses to climate change, and the choice of discount rate (Pearce 2003). Although there is a theoretically appropriate way for calculating the rate of discount that should be applied, this is likely to remain a contentious issue for the foreseeable future. Since it is possible to test the sensitivity of outcomes to the choice of discount rate, this need not be a major stumbling block. A more limiting factor is likely to be the quality of models of human adaptation to and mitigation of ecosystem change. This is an area, however, in which there is the significant potential to develop enhanced predictive models.

4.2.3. How human actions affect changes in ecosystem services and its consequences

The MA identified a number of the anthropogenic drivers of change in ecosystem services, together with a number of exogenous forcing factors. This implies that human well-being depends both on factors that are within human control and factors that are beyond our control, the balance between endogenous and exogenous factors varying with the spatial and temporal scale at which a problem is addressed. This affects both the options open to decision-makers – the balance between adaptation and mitigation – and the appropriate way of modelling future effects. Where it is possible to identify the future consequences of current actions, at least probabilistically, then it is appropriate to develop predictive models to support either mitigation or adaptation. Where it is not possible to identify the future consequences of current actions it is appropriate to develop non-probabilistic scenarios to support adaptation. While the MA was confident about the anthropogenic drivers of ecosystem change, it was not confident enough of the mechanisms involved to develop predictive models, instead opting for non-probabilistic scenario development. We note the unanswered questions raised by scenario development above. The major research challenge left by the MA is the development of predictive models to support mitigation.

Among the most significant anthropogenic drivers of ecosystem change is the increasing integration (coupling) of the global economy. Globalization affects both the rate at which species are dispersed (through trade) and the rate at which host systems are homogenized (through land use). It should be possible to generate ecologically-founded models that build on the way that biological dispersion and changes in species assemblages are currently analyzed in theoretical ecology. Integrated ecological-economic models should then be able to predict the consequences of globalization in both highly impacted agro-ecosystems and marginally impacted conservation areas. These consequences include change in the resilience of ecosystems, and hence in the regulating services offered by those systems

Resilience has two connotations (Folke *et al*. 2005): as a buffer to reduce the risk of nonlinear threshold change, and as a capacity for renewal and reorganization following a catastrophic change. In view of the multiple and mostly-unknown thresholds that arise in regional social-ecological systems, it is inevitable that some thresholds will be crossed with large persistent adverse consequences for ecosystem services and human well-being. Thus resilience in the second sense is essential. Many case studies indicate that the organization of social-ecological systems determines their capacity to reorganize and transform following a massive loss of ecosystem services and human well-being (Walker and Salt 2006) and numerous papers in the online journal Ecology and Society, http://www.ecologyandsociety.org). However, this body of research is largely composed of diverse case studies, with sparsely-tested and sometimes vaguely-articulated theories.

We recommend a programme of systematic research to understand how resilience is built in regional social-ecological systems. This research should seek patterns in diverse case studies and develop general principles for building resilience, and lead to practical, empirically-confirmed guidelines for building resilience in sensible day-to-day decision making

5. Mechanisms for the Sustainable Use of Ecosystems

5 1. Research needed to understand how ecosystem services and human well-being outcomes can be modified by human actions

It is beyond the scope of this report to present a comprehensive list of research needs, although priorities are noted, that would improve our understanding of how human actions influence ecosystems and human well-being and how those actions could be modified to achieve desired outcomes. Such a list would include priorities for research addressing specific sectors (e.g., forestry, agriculture, fisheries), ecosystems (e.g., grasslands, coastal zones), and types of interventions (e.g., institutions and governance, policy, technology, behaviour, information). Instead, we examine here a narrower set of research needs that address more cross-sectoral or emergent gaps in knowledge that we encountered in the MA due to its more holistic treatment of multiple sectors, multiple services, and multiple dimensions of human well-being.

There is tremendous variation from site to site in both ecological and socio-economic context. As a result, the interventions that can be made in policies or practices, the effectiveness of those interventions, and the outcomes that result are strongly dependent on site characteristics. This makes broad generalizations suspect, although there is much that can be learned from careful comparisons across sites. Environmental assessments that consider only one or a few issues, such as assessments focused on food production, climate change, water availability or forest loss, typically address clearly defined problems. Consequently there is little ambiguity about the nature of the interventions or system responses to be assessed. However, this narrow focus has its own weakness in that insufficient attention is given to other issues and other sectors that may be just as important to human well-being. Increased fertilizer application may make sense when viewed only from the standpoint of increasing crop production, but not when harmful consequences of increased nutrient use on water quality and fisheries are considered.

We see at least eight key research needs that would improve our understanding of how human actions could be modified to best achieve desired ecosystem and human well-being outcomes.

5.1.1 Identifying situations where important ecosystem service risks are not being adequately managed (by governments, business, etc.)

The conversion of ecosystems involves trade-offs between different ecosystem services and, without valuing the services gained and lost, it is not possible to say whether the system itself has increased or decreased in value. Many of the ecosystem services displaced in the conversion of systems to the production of marketed crops are not valued in the market place. Two things follow. First, the people converting ecosystems take no account of the ecosystem services they lose because of their actions. Second, there is no measure of the consequences for society of their actions. If people are to be confronted with the costs of their actions, or to be compensated for forgoing some action in order to confer a benefit on society, or if society is to keep track of the value of the natural assets that form part of its overall wealth, the first order of business is to obtain estimates of the value of ecosystem change.

As noted in section 4.1., the best estimates currently available are the adjusted net savings data produced by the World Bank[5]. These measure changes in the level of national savings – which is equivalent to change in the value of assets – taking into account both investment in human capital and the depreciation of natural assets (Hamilton 2005, Hamilton and Hartwick 2005). While these are an important step in the right direction, however, they are as yet limited to traditional natural resource stocks that correlate poorly to ecosystems. A number of individual countries are currently developing green accounts to capture the value of at least some ecosystem change, but these accounts are also focused on traditional stocks. Enhanced estimates of the value of ecosystem change, building on the methods of the adjusted net savings measure but extended to include the ecosystems that support the provision, cultural and regulating services, are essential component of any future assessment.

5.1.2. Develop mechanisms – such as land use taxes, payments for ecosystem services, access charges or user fees, or the removal of existing distortionary taxes – to redress the undervaluation of ecosystem services.

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Tomich (Tomich *et al*. 2001), for example, showed that extensively managed agroforests provide greater biodiversity benefits than intensive rubber tree plantations, but that at the current real producer price of rubber, relative to the minimum wage rate, returns to farm

[5] http://go.worldbank.org/3AWKN2ZOY0

labour are 70% higher in intensive plantation systems than agroforestry. Once distortionary prices, including tax and subsides for rubber production, are eliminated, however, labour returns to rubber production in extensive agroforestry systems outweigh its alternative plantation returns by 30%. Other consequences of distortionary interventions include the loss of forest and wetland habitat, the devegetation of watersheds, the loss of soil and aquatic biodiversity through the application of pesticides, nitrogen and phosphorous, the depletion of many beneficial pollinators and pest predators (Scherr and McNeely 2006), and the introduction of invasive species (Mooney *et al*. 2005). While this is an area that has attracted more attention from economists, there is still a significant research challenge in the design of appropriate mechanisms.

5.1.3. What has been the outcome of attempts to change human actions to improve environmental management?

There is a striking absence of systematic analysis and evaluation of policies and management interventions that have been put in place to address multi-sectoral environmental challenges, particularly at a landscape scale. Existing policies constitute natural experiments from which much could be learned (Campbell 1969). For example, over the past 15 years there has been a proliferation of innovative biodiversity conservation strategies designed to increase local incentives for conservation. Yet in their analysis of biodiversity responses, McNeely *et al.* (Chapter 5 in MA 2005e) conclude that "A key constraint in identifying what works and what does not work to create economic incentives for ecosystem conservation is the lack of empirical data supporting or refuting the success of any approach. …. Few rigorous and systematic empirical evaluations assess whether an existing initiative to allow people to capture benefits from biodiversity is achieving the conservation and development objectives it purports to achieve."

5.1.4. What are the impacts of interventions designed to affect a particular ecosystem service or attribute on the entire bundle of ecosystem services in a region?

Studies of human impacts on ecosystems have tended to focus too narrowly on a limited set of ecosystem attributes. The MA has shown that the unintended consequences of these interventions are often of significant importance, yet these are rarely measured or studied. Even in the cases where extensive research has been undertaken to explore policy options for individual services such as crop production, there is relatively limited research into the nature of trade-offs that may occur with other ecosystem services. A more complete understanding of the costs and benefits of alternative management approaches (including the distribution of those costs and benefits across stakeholders) for the entire range of ecosystem services is essential for the design of effective policies. This information tends to be extremely site specific in nature. To date, there appear to be no examples of complete landscape-scale assessments of the quantity, quality and value of an entire bundle of ecosystem services under alternative management regimes.

5.1.5. How do the effects of various interventions vary across ecological and social contexts?

No single policy or management intervention is applicable across all contexts: one size does not fit all. In general, the problems and opportunities we face are very site specific, as are the potential responses that might be used to address those problems. There is insufficient understanding of the preconditions that must be met in any region to grapple with these issues (a clear vision on the needs for monitoring and analyses and the human and institutional capacity to undertake such monitoring and analysis) and relatively limited understanding of planning and decision-making processes that can most effectively address these issues.

5.1.6. How do changes in "indirect drivers" influence "direct drivers" and what factors mediate this relationship?

We need a better understanding of what the MA labels "indirect drivers" of environmental change: demographic, economic, socio-political and cultural factors. Most research related to ecosystem service responses focus on direct drivers of change in services, such as land use change, climate change and invasive species. Yet effective management of particular services will require more systemic attention to indirect drivers. Improved understanding of how reforms addressing indirect drivers of change will affect the entire bundle of ecosystem services in any region are the necessary prerequisite to exploring the potential emphasis that should be given to these more systemic changes. In some cases the indirect drivers may be better leverage points for policy reforms than the direct drivers since the elasticity and plasticity of such indirect factors can be substantial. For example, the MA noted that production subsidies for agriculture and fisheries often cause market distortions. These distortions result in overharvest of certain ecosystem services and overuse of inputs that may in turn harm other ecosystem services. Nevertheless, the reduction of agricultural production subsidies in developing countries is likely to result in greater expansion of agricultural production in developing countries. The costs of this expansion for other ecosystem services in these countries, and globally, are poorly understood.

5.1.7. What opportunities exist to create markets or payment mechanisms for currently un-marketed ecosystem services that could help to pay for the conservation of the service?

The MA concluded that significant opportunities existed to apply economic incentives to enhance ecosystem service management. There have been a number of interesting experiments with market-based approaches and payments for ecosystem services that deserve careful evaluation. Such approaches may have considerable potential to enhance ecosystem management, but as yet there has been relatively limited research that can help determine the effectiveness of different approaches and thus lead to design criteria for effective incentive-based mechanisms.

5.1.8. Understanding how coupling across space and time influences the ability of human actions to achieve desirable outcomes

Better outcomes, meaning not just narrowly optimized solutions, but solutions that are resilient in the face of uncertainty (*i.e.*, optimization in the presence of risk), can only be achieved if the key feedbacks, tradeoffs and thresholds are included in the analytical framework. Given the pervasive presence of cross-scale effects and slow processes in both the ecological system and the human system, and especially in their coupled state, it follows that understanding of these links and incorporating them appropriately is a necessary condition for better outcomes. This will inevitably mean a high reliance on models, both to achieve time perspectives beyond that of the assessment, but also to understand tele-connections that are not amenable to experimentation, for either practical or ethical reasons.

A key structural problem is that the human decision-making cycle, particularly at national or global scales, may simply be too slow to achieve desirable outcomes, given the contemporary rates of change. To reduce this problem as much as possible, the delay between observation, scientific analysis and communication into policymaking needs to be shortened – a suitable iteration period between assessments, and timely attention to the findings are both indicated, as are a greater sense of urgency by all parties (and a willingness by scientists to forgo some degree of certainty for a longer warning of emergent problems).

Desirable outcomes are quite unlikely in situations of 'commons'-type problems unless there are strong institutional mechanisms at a scale appropriate to the problem. Currently, the mechanisms for dealing with issues such as global climate change, biodiversity loss and over-harvesting of marine resources lack the power of enforcement to pre-empt problems. They typically only achieve sufficient consensus for cooperative action once serious problems have emerged, and a sense of collective crises overpowers the self-interest of individual parties.

6. Monitoring and Data

The MA led to a number of conclusions that have implications for data and monitoring needs. First, the MA highlighted that ecosystem services are an important, but not the only, aspect of human well-being. Multiple other factors, related to economic opportunities, governance, and infrastructure, also contribute directly to human well-being. Moreover, the ability to purchase substitutes to replace loss in ecosystem services confounds unambiguous and observable linkages between human well-being and ecosystem services. Attributing change in human well-being to change in ecosystem services is consequently difficult in any particular situation without accounting for the full range of inter-related factors. Data collection needs to be designed to distinguish responses of human well-being to changes in ecosystem services from responses to other factors.

A second conclusion from the MA is that production functions relating a measurable condition of ecosystems (*e.g.* forest cover, soil nutrients) to the services they deliver to society (*e.g.* flood protection, sustainable crop yields) are not well known. Standard manipulative experiments are not generally applicable due to large temporal and spatial scales over which services respond to changes in ecosystem condition. Alternative approaches such as comparative analyses need to be applied. Data on the response of services to changes in condition need to be collected over wide varieties of ecological conditions and models need to be developed.

Finally, the MA highlighted that trade-offs among ecosystem services resulting from policy decisions occur across spatial and temporal scales. Most often a benefit at a local scale, such as increase in crop production or transportation access, has negative implications for ecosystem services only over longer time scales and more distant locations. A research agenda to characterize the implications across scales and across different segments of the population requires new approaches. For example, questions about responses of human well-being to changes in ecosystem services might be best addressed at local scales to account for the economic, social, and ecological context. Questions about flows of ecosystem services through trade and long-range transport might be best addressed at regional and global scales. At the global scale, identifying hotspots and syndromes of change is a feasible goal. Consequently, each scale of analysis has separate data and monitoring requirements.

These three conclusions, combined with the observation that data needs for developing theoretical understanding of ecosystem services are distinct from data needs for decision-making, suggest a data and monitoring system that: 1) observes both human and ecological variables; 2) is designed according to the scale; and 3) develops the information base for both decision-makes using the results of the MA and scientific investigations to understand linkages among human well-being, ecosystem services, and ecosystem condition. Consideration and development of systems to measure these crucial elements will provide important input into the evolving Global Earth Observation System of Systems (GEOSS).

The Group on Earth Observations (or GEO) is coordinating international efforts to build a GEOSS. This emerging public infrastructure is interconnecting a diverse and growing array of instruments and systems for monitoring and forecasting changes in the global environment. This “system of systems” supports policymakers, resource managers, science researchers and many other experts and decision-makers. Within the GEOSS context (GEO 2005), nine societal benefit areas have been identified; disasters, health, energy, climate, water, weather, ecosystems, agriculture and biodiversity. ICSU (2004) has argued for inclusion of socio-economic data in the development of global monitoring systems, something which is of crucial importance to both MA relevant research and the conduct of a second assessment.

Data and monitoring might be organized around the following needs:

6.1. Data to understand linkages between ecosystem services and human well-being.

Indicators of human well-being directly related to ecosystem services depend on regional or local conditions and vary for different segments of the population. For those segments directly dependent on local ecosystem services, important variables might address livelihood dependence on ecosystem services such as water, traditional biofuel use, and protein consumption. For more affluent segments of the population with the ability to substitute ecosystem services, a different set of variables to identify relationships with ecosystem services through trade and consumption patterns might be needed. A regional scale for data collection and monitoring might be appropriate considering the variations in social and economic ties to ecosystem services.

6.2. Data to quantify linkages between ecosystem condition and ecosystem services

To ultimately develop modelling and analytical tools to project the response of ecosystem services to changes in ecosystem condition, data and monitoring at multiple scales will be needed. At the global scale, the monitoring need is to identify hotspots or vulnerable regions where ecosystem conditions are changing. The monitoring effort would identify such locations for more in-depth analysis. Land cover change and changes in marine productivity, for example, need to be monitored at a global scale, in order to identify the regions and types of response in ecosystem services. Regional monitoring of land management or fertilizer use within river basins or air sheds, for example, might also address responses of ecosystem services to changes in ecosystem condition that occur upstream or more distant in space.

6.3. Data for immediate decision-making by users of the MA

Immediate decision-making needs at the global scale relate to identifying the most vulnerable locations where declines in ecosystem services potentially have negative impacts on human well-being, or where changes in ecosystem conditions have potentially catastrophic impacts on ecosystem services. Variables such as primary productivity, water discharge, forest cover, and vegetation stress might be monitored at the global scale to highlight vulnerable locations where policy interventions are needed. Global monitoring also is important for tracking the effectiveness of policies such as sustainable timber initiatives.

Monitoring at local and regional scales coincides with the scale at which decisions are made. At this scale, data on indicators of human well-being that relate directly to ecosystem services might be possible, such as protein sources for coastal communities affected by declining fisheries or access to fuelwood. As different ecosystem services are important in different regions, there is not likely to be a single indicator relevant for all locations.

Aggregated indicators for ecosystem services, analogous to GNP, atmospheric carbon dioxide concentration, or the human development index, have been elusive. Such indicators are critical for decision making to identify when and where policy interventions are needed. Whether such an index should be based on availability of ecosystem services (water, food, soil nutrients, fisheries, fuelwood), ecosystem condition (land cover, ocean productivity), or human well-being (nutrition, time spent collecting ecosystem services, health outcomes) needs further consideration. Indicators that relate directly to human well-being would likely have direct utility to decision makers in deciding where and when interventions are necessary.

7. Improving Mechanisms whereby Knowledge can most Effectively Contribute to Decision-making

The most important barriers to the more effective use of knowledge concerning ecosystem services in decision-making are the lack of landscape-scale information about the flows, values, and uses of ecosystem services and the lack of knowledge of the “knock on” effect of a change in one ecosystem service on other ecosystem services in a particular area. Most existing studies of ecosystem services have focused on specific services in specific regions. In contrast, in order to make sound decisions concerning ecosystem services, a decision-maker typically must understand the flows and values of the entire bundle of important services in a particular region and how any proposed intervention might affect the full set of services. Several of the MA Subglobal assessments attempted to provide this analysis for a subset of ecosystem services, and research is now underway in other regions (*e.g.,* the TNC/WWF/Stanford Natural Capital Project—www.naturalcapitalproject.org), but currently the demand for this type of information greatly outpaces the supply.

By way of analogy, conservation planning and decision-making underwent a revolution in the 1970s and 1980s when it became commonplace to work with comprehensive maps indicating patterns of species richness and endemism. The data underlying such maps ranged from detailed inventory work (*e.g*., the Natural Heritage programmes of The Nature Conservancy in the United States), to the best available information and judgment of field biologists (*e.g.*, early efforts to map conservation priorities in Amazon region). Most countries and often states or provinces and counties now typically have relatively fine-grained information on patterns of diversity, sensitive habitat areas, and endangered or threatened species that can inform both conservation priority setting and priority setting for infrastructure or other development.

What is now needed is a similar revolution in the form of adding layers to such maps detailing ecosystem service sources and flows related to factors such as water quality, carbon sequestration, flood protection, pollination, fisheries rearing, storm protection and other valuable services (forthcoming special issue of Frontiers in Ecology and Environment, 2008). Until these basic data are available in a form that can be used by decision-makers, it will be impossible for the concepts to usefully inform decisions.

Even when appropriate data are available, the process by which information concerning ecosystem services and human well-being is conveyed to decision-makers is critically important. One key lesson that applies at both the local and the global scale is that early engagement of decision-makers in the design and conduct of studies or assessments of ecosystem services greatly increases the utility of the resulting information. At a local level, the involvement of local stakeholders is essential in helping to define what features of the environment and ecosystem are of greatest importance to the local community. Similarly, at a global scale, the direct involvement of decision-makers is needed to help define the key policy-relevant questions that data should be mobilized to address. Work is now also underway with private companies through organizations such as the World Resources Institute and the World Business Council for Sustainable Development to help firms evaluate their impacts on ecosystem services and business risks associated with ecosystem services (Hanson *et al.*, 2008). Here again, the specific definitions of target services and the specific questions that need to be addressed can only be developed with the active engagement of the relevant business managers.

A clear need exists at the global scale for a periodic assessment of the consequences of ecosystem change for human well-being and of opportunities to change policies or practices to enhance ecosystems and human well-being. The MA was designed as a pilot assessment that, if it proved useful, was expected to catalyze the creation of a periodic assessment process similar to the Intergovernmental Panel on Climate Change (IPCC) although perhaps with a somewhat longer interval of time between assessments. Periodic assessments like the IPCC are far more helpful to decision-makers than one-off assessments because:

- They enable patterns of change to be monitored over time, thereby detecting trends and making it possible to detect when interventions are altering those trends;
- Research carried out during the intervening years between assessments can help fill gaps in data and understanding, creating the conditions for continuous improvement in the supply of policy-relevant information;
- The assessment process builds credibility and stature with time, as well as visibility among the media and NGOs; and
- In the long run, an important constraint that will hinder the flow of knowledge concerning ecosystem services to decision-makers is the relatively weak research, monitoring, and assessment capacity in this field. Much of the research in this field is inherently interdisciplinary and consequently faces greater funding constraints than in other related fields. And the existing pool of experts involved in some of the most critical research areas, such as economic valuation of ecosystem services, is extremely small to begin with.

8. A New Research Agenda

The UK House of Commons Environmental Audit Committee has reviewed the MA (Commons 2006) and one of the recommendations was:
"To enable the MA knowledge gaps to be filled a new international interdisciplinary research strategy must be established to help coordinate research at a number of scales. This could be hosted by the ICSU, or ultimately within a new body to oversee a rolling programme of MA assessments". (Paragraph 61)

The Terms of Reference for the ICSU-UNESCO-UNU Group (Annex 2) included "to consider whether scientific progress will best be achieved through a decentralized bottom-up approach, regional foci through research/assessment projects, and/or an internationally coordinated research effort". This Group has come to the conclusion that, in addition to the many decentralized research efforts already underway to look at ecosystem services, as noted earlier, it would be important to also launch a new programme consisting of a number of sites using criteria for sub-global assessments that would be selected on the basis of their value in a network of coordinated research sites to address the link between ecosystem services and human well-being.

8.1 Elements of a research agenda

The fundamental research challenges identified through the work on the Millennium Ecosystem Assessment relate to the need to understand the integrative and dynamic nature of the interactions of drivers, ecosystems, and human well-being. The gaps in understanding that exist today are evidence of the fact that those fundamental challenges cannot be adequately addressed through uncoordinated studies of individual components human-ecosystem interactions in an ad hoc set of research sites scattered across the globe.

We propose the establishment of a global research initiative that could build upon and strengthen existing global change research programmes such as DIVERSITAS, the International Human Dimensions Programme on Global Environmental Change (IHDP), and the International Geosphere-Biosphere Programme (IGBP), with a mission of **fostering coordinated research to understand the dynamics of the relationship between humans and ecosystems**. The initiative would be time-bound (10 years) and intended to stimulate a major advance in understanding of these critical issues, but not intended to become a continuing global change research programme. The initiative would seek to answer the most fundamental and policy-relevant questions concerning factors driving changes in ecosystem services, the impacts of those changes on human well-being, and opportunities to better manage human use and impacts on ecosystems.

The Millennium Ecosystem Assessment conceptual framework would provide the necessary coherence for such a research initiative by enabling coordinated analysis across the full framework of drivers, ecosystems, services and human well-being and across spatial and temporal scales. The research initiative would focus on the research questions highlighted in this report. By careful selection of scales, locations, and topics, the initiative could greatly extend our understanding of the dynamics of the relationship between humans and ecosystems and as well as the coupling of systems across temporal and spatial scales. At the same time, it would help to build a body of empirical research on issues such as valuation, regulating services, thresholds, drivers and other topics that could greatly enhance the ability of the scientific community to inform policy and management decisions related to ecosystem services.

Such an initiative should enhance understanding of: a) the nature of interactions among drivers; b) the relative influence of ecosystem change on human well-being; c) interactions among ecosystem services; d) cross-scale (temporal and spatial) interactions of drivers, services, and responses; e) how ecosystem services and human well-being outcomes can be modified by changes in policies or management; and, f) how to model the relationship between humans and ecosystems at local, regional, and global scales. Such an initiative would be best structured around two basic components.

8.2 The research foci

Regional foci: First, research teams would undertake coordinated work in a set of five to ten core regions, chosen so that the set of regions would provide the best set of contrasts and, where possible, would build on a strong existing base of scientific expertise and data. These regional research activities would focus on understanding the full dynamics (across spatial and temporal scales) of the relationships among drivers, ecosystems and human well-being and understanding the trade-offs among ecosystem services. Although focused on the key research questions, each such regional project would ideally aim to produce shorter-term outputs (e.g., within 5 years) of information directly relevant to decision-makers and would also build capacity in the region to study, monitor, and manage ecosystem services. The research initiative would logically begin with a pilot in one or two regions then expand to the full set of core regions after methods and protocols had been established and tested. Additional research teams could join such a network if they agreed to use comparable protocols.

Global issues: Second, research teams would undertake work at the global scale, in partnership with DIVERSITAS and other global change programmes, on the global drivers of change in ecosystem services, and the global implications of ecosystem service change at multiple scales. Topics to be addressed at this level include: a) the feedbacks between biodiversity change at multiple scales and global ecosystem services , especially the globally regulating services; b) non-linear and abrupt changes in drivers, ecosystems, and ecosystem services; c) the implications of displacement of drivers and ecosystem service flows through space and time as a result of trade and markets; d) the global risks of trade-induced species dispersal; e) global ecosystem governance and risk-management options; f) global modelling of the impact of drivers on ecosystem services and the impact of changes in services on human well-being at multiple spatial and temporal scales.

We described the challenge facing human society as being of 'unprecedented proportions'. Meeting that challenge will require unprecedented cooperation in the management of the global commons. It will also require unprecedented information flows on the performance of the global system. A targeted and integrated research programme, as described, would give us the knowledge of how best to evaluate the full benefits that society is deriving from ecosystems, locally and globally, and how to insure that these benefits are sustained in the face of increasing pressures on the systems that provide them.

8.3 Potential interaction with other major initiatives

8.3.1 DIVERSITAS

The DIVERSITAS international biodiversity science programme is one of four international global environmental change programs, the others being the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP) and the World Climate Research Programme (WCRP), all sponsored by ICSU. DIVERSITAS comprises a set of core projects that span systematics, monitoring and assessment, genomics, evolutionary biology, ecology, microbial biology, economics and governance of biodiversity and ecosystem change: bioGENESIS, bioDISCOVERY, ecoSERVICES and bioSUSTAINABILITY. The core projects are complemented by a series of cross-cutting networks that address specific issues spanning two or more core projects. These include networks on biodiversity in agriculture (agroBIODIVERSITY), freshwater aquatic systems (freshwaterBIODIVERSITY), montane systems (Global Mountain Biodiversity Assessment) and invasive species (Global Invasive Species Program). A new network on biodiversity and health (bioHEALTH) is currently in development. DIVERSITAS focuses on the interactions between biodiversity change and change in other components of both the geophysical and social systems.

The framework developed in the Millennium Ecosystem Assessment reflects DIVERSITAS' focus on the interlinkages between human well-being and ecosystem change. In particular, the MA concern with the benefits that people derive from the biodiversity and the supporting, regulating, provisioning and cultural services of ecosystems maps into the research being undertaken by the ecoSERVICES core project and the cross cutting networks with which it is most closely associated - agroBIODIVERSITY, freshwaterBIODIVERSITY and bioHEALTH . Enhancement of the knowledge base of biodiversity and its interactions with the abiotic components of the global system maps into the research being undertaken in the core projects bioGENESIS and bioDISCOVERY and the work by the Group on Earth Observations (GEO) on the development of a Global Environmental Observing System of Systems (GEOSS). It has been noted above that ICSU (2004) has argued for inclusion of socio-economic data in the development of global monitoring systems. There is scope for DIVERSITAS to provide the link between earth observation and observations on the social consequences of resulting changes in the delivery of ecosystem services.

Given a shared vision of the way that ecosystem and societal change are connected, it is clear that there are many potential synergies between the MA follow-up and DIVERSITAS. A number of the unresolved scientific questions elaborated in the MA follow-up exercise are already on the agenda of one or more of the DIVERSITAS core projects, and this offers scope for collaboration at several levels. A number of others are not yet on the agenda of any of the global change programmes, but it is anticipated that the exercise will help guide development of the scientific agenda going forward. Two examples of this follow.

Engaging science in 'social' experiments on coupled social-ecological systems at the landscape level: Past scientific experiments on the effects of biodiversity on ecosystem processes have been made at smaller scales than those at which ecosystem services are delivered. They have typically taken place in a restricted set of ecosystems, have involved only plants, and have not contemplated interacting factors (Díaz *et al*. 2007). Many 'social experiments' that impact ecosystem services by changing biodiversity occur at the landscape scale, affect multiple trophic levels, several ecosystem services and have potentially irreversible consequences. Their potential effects cannot be demonstrated through isolated, small-scale scientific experiments because of the importance of system-level feedback effects. Science is only weakly engaged in the decision-making associated with most of these 'social' experiments – through some variant of environmental impact analysis or assessment. Strengthening engagement of science in the decision-process requires a different approach and a different set of protocols than those that apply to small scale scientific experiments. The MA follow-up and DIVERSITAS may jointly be able to develop the design protocols for 'social' experiments impacting biodiversity and ecosystem services across multiple national jurisdictions.

Enhancing predictive modelling capacity: Experiments on the behaviour of many complex systems takes the form of perturbations of models of those systems. Progress has been made in modelling the general circulation system, but the biosphere and its interactions with the social system are still very poorly represented. It has already been observed that to enhance our capacity to predict the adverse consequences of current activities for ecosystem services we need models that address feedbacks, discontinuities and other interactions among multiple ecosystem services simultaneously, in response to combinations of stresses at global and regional scales. These models need to address the system-level linkages between drivers, feedbacks, ecosystem services, economic valuation and human well-being indicators. The scale of effort required to make progress in this area is such that multiple partners will be needed. The MA follow-up and DIVERSITAS might naturally anchor that effort.

8.3.2 UNESCO Man and the Biosphere Programme

In 1971, UNESCO launched an intergovernmental programme to deal with the study of human impacts on the biosphere and how to 'reconcile' this relationship – the Man and the Biosphere Programme (MAB).

The MAB Programme grew from a knowledge and research project network into one that also encompasses field sites used for interdisciplinary research, observations and assessments. These sites are more than 500 and are located in more than 100 countries; together, they constitute the World Network of Biosphere Reserves (WNBR).

Biosphere reserves are entire portions of the territory. They do not exclude people but rather encompass ecosystems, people, ecological services, and both adverse as well as beneficial actions of people on the environment. Their size span from very limited to very large in size (in the range of 290 to almost 30 million hectares). They reflect a whole gradient of both ecological and socioeconomic conditions. Some of them have been established more than 25 years ago, while others are most recent. As such, they constitute ideal sites for conducting field research.

Several biosphere reserves under the MAB Programme participated directly or were relied upon in the context of the Millennium Ecosystem Assessment (MA). The Sao Paolo Green Belt Biosphere Reserve is one of them. The MA comprises more than 30 citations of sites that are biosphere reserves and in which research important to deliver the MA had been conducted.

Examples of research conducted in biosphere reserves that can be useful from the stand point of filling some of the knowledge gaps pointed at by the MA can be found in relevant scientific journals on a regular basis. Hundreds of references based on research carried out in biosphere reserves in the areas of global change, climate change, biodiversity, soil degradation and fertility as well as several branches of social science are available in the scientific literature. Many technical publications and the news sections of scientific journals have illustrated the societal relevance and applications of research carried out in biosphere reserves.

The MAB Programme, including the WNBR, relies on a related action plan for its implementation. The governing body of the MAB Programme adopted the latest version of such a plan – the 'Madrid Action Plan' (MAP[6]) – in Madrid in February 2008. The MAP is organized around three main areas: climate change, provision of ecosystem services and globalization as a main driver of change.

It is recommended that biosphere reserves be used, as appropriate, for future research aimed at filling knowledge gaps identified by the MA.

9. The Way Forward

The ICSU Executive Board has recommended to the ICSU General Assembly (October 2008) to establish a major new interdisciplinary programme of ten years' duration entitled Ecosystem Change and Human Well-being, to recognise this programme as an Interdisciplinary Body and request the Executive Board, in consultation with UNESCO and UNU, to establish a Scientific Committee for the programme. ICSU will also continue involvement with key partners in continued implementation of the findings of the Millennium Ecosystem Assessment and the preparation for a new global assessment on ecosystem services and human well-being.

The Scientific Committee will establish criteria for site selection, work with partners and stakeholders to define in some detail the co-ordinated research that will be conducted at each site, dialogue with funding bodies for scientific research and donor agencies to assist with funding for the research sites, provide a synthetic framework for inter-site analysis and synthesis, ensure proper coordination with current and future sub-global assessments that use the MA conceptual framework and provide scientific guidance for the overall programme.

It is expected that an International Programme Office will be established and offers to host such an office will be sought. It is expected that the programme, together with the global change research programmes sponsored by ICSU, in particular DIVERSITAS, will provide the research basis for the proposed Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

[6] http://www.unesco.org/mab/madrid/doc/E_MAPfinal.pdf

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11. List of Acronyms

CBD	UN Convention on Biological Diversity
DFID	Department for International Development (UK)
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GNP	Gross National Product
HDI	Human Development Index
HIV	Human Immunodeficiency Virus
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme (ICSU)
IHDP	International Human Dimensions Programme on Global Environmental Change (ICSU, ISSC)
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	Intergovernmental Panel on Climate Change
ISSC	International Social Science Council
ISTS	Initiative on Science and Technology for Sustainability
IUCN	The World Conservation Union
MA	Millennium Ecosystem Assessment
MAB	Man and the Biosphere Programme (UNESCO)
MAP	Madrid Action Plan (MAB-UNESCO)
NGO	Non-Governmental Organization
SARS	Severe Acute Respiratory Syndrome
SMS	Safe Minimum Standards
TWAS	The Academy of Sciences for the Developing World
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNU	United Nations University
WCRP	World Climate Research Programme (WMO, ICSU, IOC)

WMO	World Meteorological Organization
WNBR	World Network of Biosphere Reserves (MAB-UNESCO)
WRI	World Resources Institute

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Annex 2

Terms of Reference for a Millennium Ecosystem Assessment Science Follow-up Group

One of the recommendations from the Millennium Ecosystem Assessment (MA) Partners Meeting in Kuala Lumpur in September 2004 was that ICSU and UNESCO should take the lead in addressing how the experiences from the MA could help identify needs for additional research that could fill some of the knowledge gaps identified by the Assessment. The need for such an analysis has also been stressed in the follow-up discussions in relation to the development of a proposal for a GEF Medium Size Grant. UNU has later agreed to join ICSU and UNESCO in this follow-up activity and it has been decided to move forward despite the uncertain fate of the GEF proposal.

The MA involved a large number of scientists worldwide and through the assessment process it was realized that sufficient scientific knowledge was not always available both at the sub-global and global levels.

There is a seamless link between research and assessments. The development of a science agenda will hopefully stimulate the science community to conduct additional research to address key issues in linking ecosystem services and human well-being. This is still a new area of research, which is hampered by universities and funding agencies often not structured in such a way as to stimulate research on the links between ecological and social systems.

There are several initiatives, such as the Earth System Science Partnership (the four global change research programmes of ICSU and others), the Resilience Alliance, UNESCO-MAB, etc, that already exists and contribute substantially in engaging the international science community. In addition, ICSU with partners published a report on Science, Technology and Innovation for Sustainable Development (ICSU-ISTS-TWAS, 2005) as a follow-up to the World Summit on Sustainable Development.

The development of a science agenda based on experiences from the MA should build on, and involve scientists from, the sub-global assessments. The initiative could also help stimulate the development of new sub-global assessments by engaging the science community in reflections over research needed to assess linked ecological-social systems. During the 2004 consultation, it was recommended that the following actions were especially urgent as follow-up to the MA:

1. A methodological handbook, currently developed by WRI, was considered by the MA Board as the highest follow-up priority. This document will also be essential for stimulating further sub-global assessments;
2. The “main-streaming” at the national level through the World Bank Institute, UNDP and others;
3. A coordination function to be established for a limited period of time to maintain the enthusiasm among the sub-global assessment and help stimulate the

development of new ones in important systems not covered by the formal MA assessments;

4. An assessment of the gaps in scientific knowledge identified through the MA process. This priority is addressed through this document.

Thus, all four follow-up components are intimately linked and all necessary to ensure the use of the MA results both by the science community and non-academic end-users.

ICSU, UNESCO and UNU will convene a Scoping Group of experts with relevant natural and social science disciplinary competence representing experiences from the MA as well as the relevant sub-global assessments to produce a report on the priority research gaps that need to be filled in order to improve any future global or-sub-global Millennium Ecosystem Assessment.

The Scoping Group shall:

6. Based on the outcomes of MA in general, and two synthesis papers that have been developed in particular, identify key knowledge gaps that should be filled through additional scientific research;
7. Prioritize research needs and indicate, whenever possible, the need for research at global *versus* regional scales;
8. Consider whether scientific progress will best be achieved through a decentralized bottom-up approach, regional foci through research/assessment projects, and/or an internationally coordinated research effort;
9. Suggest ways by which a research agenda could be further developed to address the identified priority knowledge gaps; and
10. Discuss and agree on possible mechanisms for implementing research to fill targeted knowledge gaps.

The report will be transmitted to ICSU, UNESCO and UNU. If the report recommends further development of international and/or regional coordinated approaches, ICSU, UNESCO and UNU will engage the wider science community and other potential MA partners (e.g., IUCN, WRI, etc.) to consider appropriate mechanisms to develop a science and implementation plan, related time schedules, resource needs and possible partnerships, to address the identified research gaps.

It is envisaged that the small group of experts will be convened soonest and that a first meeting should be arranged in the latter part of 2006. It is anticipated that most developments will be conducted through electronic communication and conference calls. However, at least one more meeting will be convened to agree on the final report, which should be finished before mid-2007.