Toward an Integrated Ecology and Economics of Land Degradation and Restoration: Methods, Data, and Models

Report to the ELD Project

Data and Methodology Working Group

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Executive Summary

The Economics of Land Degradation (ELD) Initiative is a global study on the economic benefits of land and land-based ecosystems. It highlights the potential costs and benefits derived from the adaptation of sustainable land management practices, and seeks to establish a global approach for analyzing the ecology and economics of land degradation, restoration, and sustainable management.

The outputs from the ELD Initiative include multiple reports based on state-of-the-art research provided by a world-wide network of researchers, practitioners, and other shareholders aimed at the ELD target groups, namely: scientific communities, political decision-makers, local administrators and practitioners, and the private sector. They will inform the debate about development policy, food security, sustainable economy, and rural development in a post-Millennium Development Goals environment. To achieve this, the initiative will build an integrated tool set for policy-makers and practitioners that can be used to analyze and evaluate a range of potential scenarios at multiple spatial scales, from farms to watersheds, and nationally to globally.

This report assesses existing data, models, and knowledge methods and recommends a way forward for the entire Initiative. It draws from existing research, publications, and case studies to summarize current practices and identify knowledge gaps. It complements the effort of the other two working groups, *Scenarios* and *Options and Pathways for Action*, and builds on the existing knowledge of the ELD Scientific Interim Report and Business Brief. This report begins with a review of the methods to value land-use and management options. It emphasizes the overall development goal of sustainable human well-being, not merely growth of the market economy. To obtain sustainable well-being through improved land management depends on the interaction of four basic types of capital assets: built, human, social, and natural. For example, the value of ecosystem services is the relative contribution of natural capital in combination with the other three types of assets to produce sustainable well-being. Although this report focuses on natural capital and ecosystem services, it recognizes that the understanding, modelling, and valuing of ecosystem services requires an integrated, transdisciplinary approach which includes all four types of capital and their complex interactions.

Assessing human well-being requires extensive data on all four types of capital at multiple scales. This report reviews availability of this data in spatially explicit form. While a huge amount of data is currently available, it is scattered and requires consolidation and reformatting to be useful for integrated modelling and analysis. Another central part of this report is a review of computer models that could be useful for analyzing and valuing land management options. This includes farm and site scale models, watershed and regional scale models, climate change models, integrated global models, and ecosystem services models.

A major conclusion of this report is that truly integrated models (i.e., models that include all four types of capital and their interactions at multiple scales) are required to meet the goals of the Initiative. Examples of these types of models do exist, but further development is necessary to make them accessible to stakeholders and used in decision-making. For further development and integration of the models themselves, a more participatory approach to model development is recommended along with the possibility of adding advanced gaming interfaces to the models to allow them to be “played” by a large number of interested parties and their trade-off decisions (and the valuations they imply) to be accumulated and compared.

This report concludes with a vision of what these integrated assessment and valuation tools might look like and how they would help solve the problems of land degradation, restoration, and sustainable management.

Introduction

It is becoming increasingly evident that allowing land to degrade is expensive, both to local owners and society in general, locally and globally, in the short term and especially in the long term (Costanza et al. 1997, Bateman et al. 2013, Trucost 2013, Von Braun et al. 2013, Costanza et al. 2014). The United Nations Convention to Combat Desertification (UNCCD) at RIO+20 set a target of zero net land degradation (ELD-Initiative 2013). The need to restore degraded lands and prevent further degradation, and, is especially important now, as the demand for accessible productive land is increasing as human population and consumption increase. The geography of these changes are projected to affect mainly tropical regions that are already vulnerable to other stresses, including the increasing unpredictability of rainfall patterns and extreme events as a result of climate change (IPCC 2007, Foley et al. 2011).

Land degradation is a consequence of the poor management of natural capital (soils, water, vegetation, etc.). Better frameworks are needed to quantify the scale of the problem globally, calculate the cost of business as usual (ELD-Initiative 2013), and most explicitly and essentially, to assess the benefits of restoration. Visionary farmers and business leaders are becoming aware that ecosystem degradation may become material issues that affect their bottom line and future prosperity (ACCA et al. 2012). However, they lack the decision-making tools to develop robust and effective solutions to the problem. The development of ecological and economic data and knowledge has been accompanied by modelling and simulation techniques that enable the creation and evaluation of scenarios of alternative futures and other decision tools to address this gap (Farley and Costanza 2002, Costanza et al. 2006, Jarchow et al. 2012, Costanza et al. 2013).

The managed land surface covers more than 60 per cent of the Earth's surface and approximately 60 per cent of this, is agricultural land use (Ellis et al. 2010, Foley et al. 2011). Ecosystems contribute to human well-being in a number of complex ways at multiple scales of space and time (Costanza and Daly 1992, MEA 2005, Dasgupta 2008, Lal 2012, UNEP 2012, Costanza et al. 2013). Land degradation is a decline in the processes and productivity of these ecosystems over an extended period of time (Lal 1997, MA 2005, DeFries et al. 2012) and as defined in the ELD Scientific Interim Report (2013) results in "the reduction in the economic value of ecosystem services and goods derived from land as a result of anthropogenic activities or natural biophysical evolution". Ecosystem services, including agricultural products, clean air, fresh water, disturbance regulation, climate regulation, recreational opportunities, and fertile soils are jeopardized by the effects of land degradation, and it is a global phenomenon (Walker et al. 2002, Foley et al. 2005, MEA 2005, UNEP 2012, Von Braun et al. 2013).

There is a need to integrate agricultural production and other land uses with ecosystem preservation to avoid land degradation in the future and to begin to restore degraded lands (Acevedo 2011). This involves a standardized framework with methods to quantify and compare the extent of land degradation across political, cultural, biophysical, and managerial boundaries.

The current ELD Initiative methodology is based on the 6+1 steps action plan developed by the UNCCD Global Mechanism (ELD Initiative 2013, p42). The 6+1 steps are designed to ensure a thorough knowledge base is established for the valuation and subsequent cost-benefit analyses that is the base of the decision-making process (Table 1).

Table 1: The 6+1 methodology of the ELD Initiative (ELD Initiative 2013)

1.	Inception	Identification of the context and framework of the study
2.	Geographical characteristics	The geographic and ecological boundaries of the study area is established
3.	Types of ecosystem services	Ecosystem identification, classification, and mapping of stocks and flows
4.	Roles of ecosystem services and economic valuation	Linking the role of ecosystem services in the livelihoods and economic development in the study area. Estimation of total economic value of the ecosystem services
5.	Patterns and pressures	Identify patterns of degradation and pressures and drivers of SLM to inform scenarios. Potential revision of previous steps
6.	CBA and decision-making	A cost-benefit analysis of each scenario to assess whether the proposed land management changes have net benefits
7.	Take action	Implement the most economically desirable option(s)

This framework is intended to provide decision-makers with transparent information to adopt economically sound sustainable land management (SLM) (ELD-Initiative 2013), and to allow for the estimation of the overall benefits of addressing land degradation and implementing ecosystem restoration. Such estimates will enable businesses and policy-makers to test the economic implication of land management decisions based on a scenario-driven, net economic benefit decision-making framework (ELD Initiative, p39, fig 7). By comparing the economic costs versus the benefits of action, impacts on human well-being, and long term effects of decisions, one is equipped to choose SLM solutions. Nevertheless, there are extensive knowledge gaps in both the conceptual and procedural approach of this 6+1 step methodology (ELD Initiative 2013, p61, box 9). These deficits revolve around the different technological, environmental evaluation, policy, and institutional problems that need to be solved before actual full scale analyses can be launched. This paper reviews the methodological, data, modelling, and knowledge gaps identified by the ELD Scientific Interim report (ELD-Initiative 2013) and provides recommendations for the way forward for the ELD Initiative.

Methods for Valuing Land Use and Management

Valuation is about assessing trade-offs toward achieving a goal (Farber et al. 2002). All decisions that involve trade-offs involve valuation, either implicitly or explicitly (Costanza et al. 1997, Costanza et al. 2011a, Costanza et al. 2014). In the past, most land degradation valuations have focused on marketed goods, such as food production using commodity prices (Barbier 2000, Cowie et al. 2011, ELD-Initiative 2013, Nkonya et al. 2013). Going forward, a more comprehensive assessment of the full range of assets and services of land is necessary.

Four types of capital assets and interrelated services

A comprehensive approach for land use valuation has to encompass the economic, social, and ecological aspects of landscape development and management. In short, it focuses on human well-being in the context of the health and well-being of the overall, linked human-natural system. This linked system consists of four basic types of capital assets (Vemuri and Costanza 2006, Costanza et al. 2007):

- **human capital**, which is individual people, including the knowledge and information stored in their brains, their physical health, and their labor;
- **built capital**, which is manufactured goods such as tools, equipment, and buildings;
- **natural capital**, which is the natural world – everything that does not require human agency to be produced or maintained (Costanza and Daly 1992), and;
- **social capital,** which are the networks and norms that facilitate cooperative action, including cultures and institutions. The market and the financial system are types of social capital (Putnam 1995).

These four types of capital are all necessary elements in supporting sustainable human well-being (Figure 1) and a suitable framework to use for an initiative like the ELD. All types of capital will be influenced by the policies and management decisions, and there is a need to address the impacts and costs of each of them. Understanding the trade-offs in land management requires a holistic assessment of the effects on all four types of capital and their interactions in order to assess changes in overall human well-being.

'Ecosystem services' are benefits people derive from functioning ecosystems (Costanza et al. 1997, MEA 2005). Ecosystem processes and functions may contribute to ecosystem services, but they are not synonymous. Ecosystem processes and functions describe biophysical relationships and exist regardless of whether or not humans benefit (Boyd and Banzhaf 2007, Granek et al. 2010b). On the other hand, ecosystem services only exist if they contribute to human well-being and cannot be defined independently. Ecosystems cannot provide any benefits to people without the presence of people (human capital), their communities (social capital), and their built environment (built capital). This interaction is shown in Figure 1. Ecosystem services do not flow directly from natural capital to human well-being; it is only through interaction with the other three forms of capital that natural capital can provide benefits (de Groot et al. 2002). The challenge in ecosystem service valuation is to assess the relative contribution of the natural capital stock in this interaction and to balance the assets to enhance sustainable human well-being. Through this, one can address the limitations of understanding the value of ecosystem services in local livelihoods (ELD Initiative 2013, p61, box 9, no. 10).

This is also the conceptual valuation framework for the recent UK National Ecosystem Assessment (http://uknea.unep-wcmc.org) and the Intergovernmental Platform on Biodiversity and Ecosystem Services (http://ipbes.net).

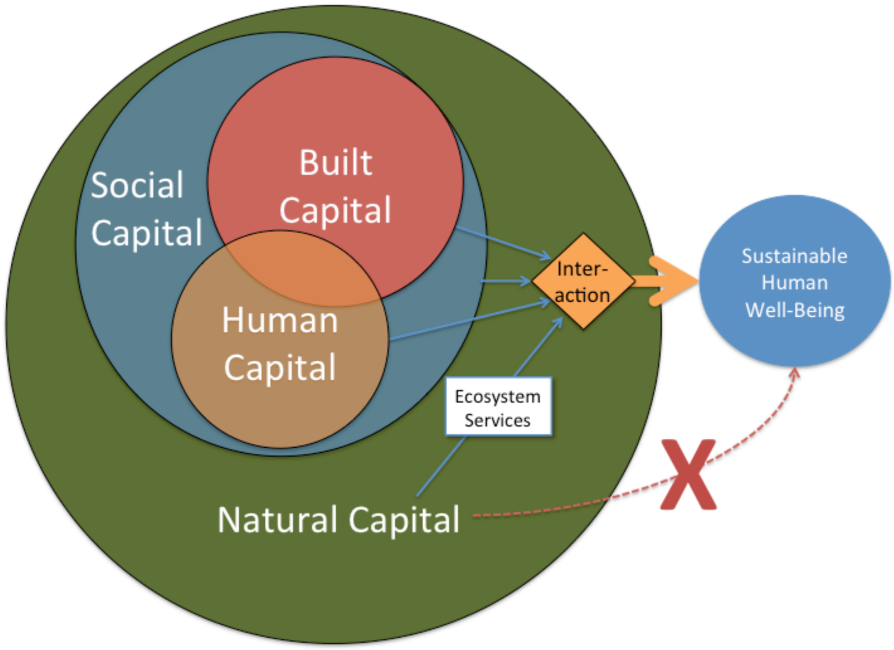


Figure 1: Interaction between built, social, human and natural capital required to produce human well-being. Built and human capital (the economy) are embedded in society which is embedded in the rest of nature. Ecosystem services are the relative contribution of natural capital to human well-being, they do not flow directly. It is therefore essential to adopt a broad, transdisciplinary perspective in order to address ecosystem services (from (Costanza et al. 2014))

There are several classification schemes that have been used for ecosystem services (Costanza et al. 1997, de Groot et al. 2002, MEA 2005, Costanza 2008, Sukhdev and Kumar 2010, Haines-Young and Potschin 2011, de Groot et al. 2012). The following categorization (used by the Millennium Ecosystem Service Assessment ((MEA 2005)) is one of the more popular. However, it should be noted that no classification scheme will work for all purposes (Costanza 2008).

a) **Provisioning services** – ecosystem services that combine with built, human, and social capital to produce food, timber, fiber, or other "provisioning" benefits. For example, fish delivered to people as food require fishing boats (built capital), fisher-folk (human capital), and fishing communities (social capital) to produce.

b) **Regulating services** – services that regulate different aspects of the integrated system. These are services that combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control, and climate control. For example, storm protection by coastal wetlands requires built infrastructure, people, and communities to be protected. These services are generally not marketed but have clear value to society.

c) **Cultural services** – ecosystem services that combined with built, human, and social capital to produce recreation, aesthetic, scientific, cultural identity, sense of place, or other 'cultural' benefits. For example, to produce a recreational benefit requires a beautiful natural asset (e.g., a lake), in combination with built infrastructure (a road, trail, dock, etc.), human capital (people to appreciate the lake experience), and social capital (family, friends, and institutions that make the lake accessible and safe). Even 'existence' and other 'non-use' values" require people (human capital) and their cultures (social and built capital) to appreciate them.

d) **Supporting 'services'** - services that maintain basic ecosystem processes and functions, such as soil formation, primary productivity, biogeochemistry, and provisioning of habitat. These services affect human well-being *indirectly* by maintaining processes necessary for provisioning, regulating, and cultural services. They also refer to ecosystem services that have not yet, or may never be, intentionally combined with built, human, and social capital to produce human benefits that support or underlie these benefits and may sometimes be used as proxies for benefits when the benefits cannot be easily measured directly. For example, net primary production is an ecosystem function that supports carbon sequestration and removal from the atmosphere and combines with built, human, and social capital to provide the benefit of climate regulation. Some would argue that these 'supporting' services should rightly be defined as ecosystem 'functions', since they may not yet have interacted with the other three forms of capital to create benefits. The authors agree with this in principle, but recognize that supporting services/functions may sometimes be used as proxies for services in the other categories.

This categorization suggests a very broad definition of services, limited only by the requirement of a contribution to human well-being. Even without any subsequent valuation, explicitly listing the services derived from an ecosystem can help ensure appropriate recognition of the full range of potential impacts of a given policy option. This can help make the analysis of ecological systems more transparent and can help inform decision-makers of the relative merits of different options before them.

The Economics of Ecosystems and Biodiversity (TEEB), and the Common International Classification of Ecosystem Services (CICES) (Maes et al. 2013), are two more recent classification schemes, each with their own strengths and weaknesses. TEEB also operates on two levels (category and service) as does the MEA, but is also built to incorporate a framework for the total economic value (TEV) of ecosystem services. This enables a consistent framework for national and regional ecosystem service assessment, valuation, and incorporation into policy (TEEB 2010).

CICES further builds on the concepts of TEEB. It is a newer classification tool developed from 2011 to 2013 by the European Environmental Agency (EEA), as an attempt to revise the System of Economic and Environmental Accounts (SEEA) (http://cices.eu) (Maes et al. 2013). CICES is a hierarchical framework that operates on five different levels (MEA and TEEB only have two levels: section and class), to encompass the needs of cross-referencing between disciplines, such as spatial sciences, environmental accounting, and economics (Maes et al. 2013).

The CICES categories parallel the TEEB classification but are tailored for economic valuation, and the TEV-methods are as applicable to this framework as to TEEB. The CICES framework offers a more detailed definition of function and processes of services, with 48 listed as compared to only 22 in TEEB (Maes et al. 2013). It can be argued that there is no need for any more complexity and categories of ecosystem services, but there are some inherent benefits to this framework. For the large scale comparisons like the ELD Initiative it could be valuable because it allows for increasing transparency of methodology, e.g., in mapping of services. Increasing the complexity may be valuable for determining the types of ecosystem services in Step 3 of the 6+1 methodology, but also for communication with and between stakeholders. Furthermore, the hierarchically specified definition of the services may increase comparability between scales and sites.

Mapping the Capital Assets and Interrelated Services

To determine the geographical characteristics of the analyses, as mentioned in Step 2, or the type and state of service stocks and flows in Step 3 and context in Step 4, as well as increasing knowledge on the low cost methods for environmental evaluation (ELD Initiative, p42, and p61, box 9), access to spatially explicit representation of human, built, natural, and social capital is fundamental. The spatial context and proximity have a significant influence on many of these interactions (Costanza et al. 2008). Reliable, spatially explicit, and valid data covering these four broad areas, as well as the interrelated flows that stem from the assets, namely ecosystem services, would provide a fundamental knowledge base from which to conduct analyses to drive actionable policies and decisions. There has been a lot of work done to collect knowledge on the state of the four capitals, the indicators of land degradation, and much of it is readily accessible. The following is a suggestion of baseline data and databases required for this task:

Human Capital

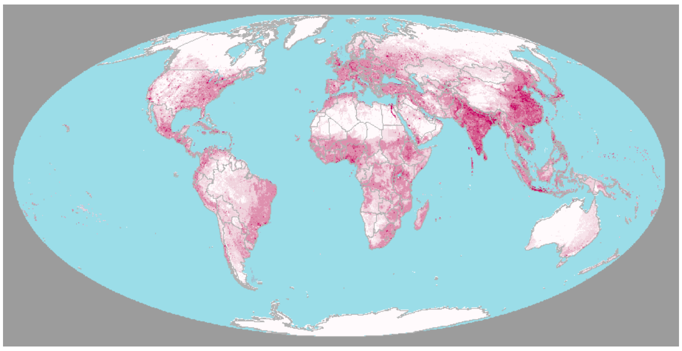


Figure 2. Human population density (Landscan)

Human capital is traditionally defined as human qualities (Sen 1997). Although the initial emphasis was on education and experience, in recent times the definition of human capital has broadened to: the productive investments embodied in a person in the form of skills, abilities, knowledge, and health, often resulting from expenditure on education, on-the-job training, and medical care (Todaro and Smith. 2012).

The United Nations Development Programme (UNDP) has emphasized the significance of human capital as part of defining human development, which is itself defined as a process of enlarging people's choice (UNDP 1990). The Human Development Index (HDI) has been considered as a better measurement than GDP growth for human development. It includes both components of human capital and is commonly used as its indicator.

Under HDI, the common indicators for knowledge, defined as an 'education index', are: (1) the adult literacy rate, defined as the percentage of population aged 15 years and over who can both read and write with understanding a short simple statement on his/her everyday life, and (2) the gross enrollment ratio, defined as number of pupils or students enrolled in a given level of education, regardless of age, expressed as a percentage of the official school-age population corresponding to the same level of education. Since 2010, the education index also includes mean years of schooling and expected years of schooling. Mean years of schooling measures average number of years of education received by people ages 25 and older, converted from education attainment levels using official durations of each level. Expected years of schooling is defined as the number of years of schooling that a child of school entrance age can expect to receive if prevailing patterns of age-specific enrolment rates persist throughout their life. All four indicators are available from UNDP dataset at national levels. In addition, UNDP datasets also holds data on the percentage of population who have successfully completed the final year of a level or sublevel of education in science and engineering, which can used an indicator for educational attainment. In addition to life expectancy, which is used for the longevity index under HDI, under-5 (years of age) and maternal mortality rates are known measures of health at a national level.

The availability of human capital depends on the total population of a country, and more importantly, on the number of people who could potentially be economically active. An economically active population is measured as percentage of population between the ages of 15 to 64. In a recent report, the World Economic Forum (Forum 2013) outlines a broader definition of human capital, based on which a human capital index is developed at the national level. In addition to current measures of human capital, education, health and employment, the human capital index adds another indicator termed an 'enabling environment'. This indicator captures factors like legal frameworks and infrastructure, which enhance the core components of human capital.

Human capital also depends on other characteristics of the population of a country, including age distribution. These characteristics are mostly identified at national levels; to obtain similar subnational spatially explicit data, other sources must be applied. An interesting source is Landscan, a global grid representation of population density produced annually by researchers at the Oak Ridge National Laboratory (http://web.ornl.gov/sci/landscan). This data is derived from census data from all nations for which it is available, and is allocated to grid cells based on transportation infrastructure, slope, elevation, and land cover. This becomes the fundamental data layer that represents 'ambient population density' (Figure 2), a temporally averaged representation of human presence. The dataset can be augmented with national and sub-national measurements like those mentioned above. However, these figures are for population density only and will have a significantly different appearance if also weighted by national statistics associated with human capital (e.g., education, life expectancy, infant mortality, etc.). Landscan is available at a global scale and a sub-national spatial resolution of 1 km^2 grid cells.

Built Capital

Just as human capital can be represented primarily via a global population density grid; built capital can be represented using global nighttime lights. 'City Lights' data products are derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS) and the Visible Infrared Imaging Suite (VIIRS) (http://ngdc.noaa.gov/eog/). They are available as global 1 km^2 grids with annual temporal resolution, dating back to 1992. 'Nighttime Lights' (NTL) data products have been demonstrated to be good proxy measures of economic activity (Costanza et al. 2011b), building volume (height and density) (Frolking 2013), GDP (Henderson 2012), impervious surface (Elvidge et al. 2007), and the human ecological footprint (Sutton et al. 2012). This data can be augmented with global radar imagery that informs building volume and other datasets such as: digital elevation models, national boundaries, and affiliated national statistics. Built capital can be further represented in several conceptual frameworks at sub-nationally gridded spatial resolution. Built capital and human capital can be highly correlated in space, and have previously been aggregated to reduce complexity in some analyses (Vemuri and Costanza 2006).

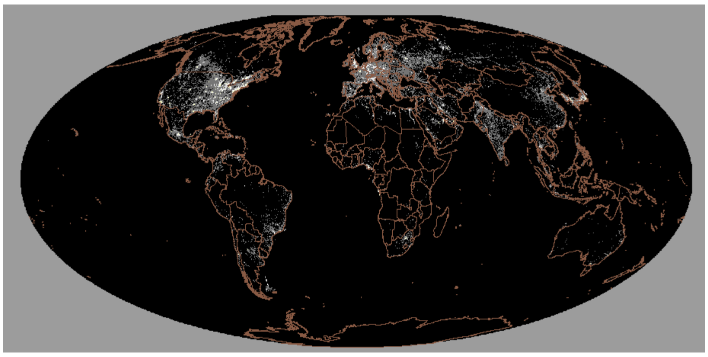
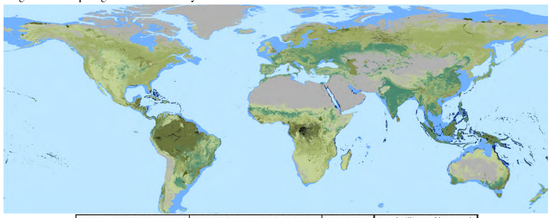


Figure 3. Nighttime Lights as a proxy for built capital

Natural Capital

Ecosystems are often measured as the amount of each type of land cover, e.g., forest, tundra, or grassland. For national level mapping, there are several global land cover datasets which provide basic substrates for representing natural capital, e.g., GlobCover (http://due.esrin.esa.int/globcover) or the Food and Agriculture Organization's (FAO) land cover dataset Global Land Cover-SHARE (http://glcn.org/databases/lc_glcshare_en.jsp). In short, when derived from best available data for the land covers and associated with ecosystem services that have significant valuation studies (Costanza et al. 1997), the global representation of natural capital is readily available at 1 km^2 spatial resolution. The temporal resolution for this sort of data requires updates every 5 to 10 years. Of course, local and regional changes can be measured and documented at higher temporal and spatial resolution. A global 1 km^2 dataset has been prepared from GlobCover, ReefBase (http://reefbase.org/main.aspx), and bathymetry data (also accounting for coral reef, continental marine shelf, open ocean, etc.), and is published as a representation of the current total global value of nature's services (Figure 4) (Costanza et al. 2014).

Figure S1. Map of global annual ecosystem services based on 2011 land areas and 2011 unit values



LandCover	Flow Value per Hectare per year	Legend	Area (millions of hectares)
Desert	$0		2159
Tundra	$0		433
Ice/Rock	$0		1640
Open Ocean	$491		33200
Marine Shelf	$2,222		2660
Grass/Rangelands	$2,871		4418
Temperate/Boreal Forest	$3,013		3003
Lakes/Rivers	$4,267		200
Tropical Forest	$5,264		1258
Cropland	$5,567		1672
Urban	$6,661		352
Swamps/Floodplains	$25,682		60
Tidal Marsh/Mangroves	$193,845		128
Coral Reefs	$352,249		28

Figure 4. Ecosystem services value (Costanza et al. 2014)

Social Capital

Most of the empirical literature on social capital focuses on community level or meso-level measures of trust, networks, and collectivism (Putnam 1995). There are many ways to conceptualize social capital including: levels of corruption, effectiveness of government, socio-economic resilience of a population, community, culture, institutions, and levels of collectivism and trust.

The World Values Survey (http://worldvaluessurvey.org) provides country level data for a range of indicators for both collectivism and trust. Collectivism can be measured as active membership in religious, political, labor union, professional, environmental, sports or recreational, art/music/educational organizations.

Datasets from the UNDP, both from the HDI and other reports (available at for instance UN data http://data.un.org/Default.aspx) includes information on trust in people and perceptions of safety, both of which can be used as a measure for trust. Surveys like the Likert-scale questionnaire[1] allows for measurements of trust for family, neighborhood, friends, and people from different religions and nationalities.

Representing social capital as a spatially explicit data set is a challenging task, as social capital is embedded in relationships between and amongst individuals and institutions. Data on fixed line and mobile telephone subscribers, measured as the sum of telephone lines and mobile subscribers and expressed per 100 people, can be used as a proxy measure for social networks. Figure 5 shows one potential way of doing this, via Facebook connections. Other options could include the Global Submarine Cable map or flight connectivity maps.

[1] In this type of questionnaire people are asked "Could you tell me for each whether you trust people from this group completely, somewhat, not very much or not at all?"

Figure 5. Facebook connections as a proxy for social capital (© Paul Butler, Facebook 2010)

Other Spatial Data Bases for Land Use and Degradation

Large databases from major organizations such as the OECD, World Bank, or FAO hold vast amounts of information (see Appendix A), and are repeatedly used for large scale analyses like the Better Life Index (OECD) or Human Development Report (UNDP). Most of this data is available on national scales, and some datasets are available at a finer scale, such as 1km^2. If the scale of data is sufficient enough, these databases could suit this analysis too. This is the case for the extensive Global Agro-Ecological Zones (GAEZ) database from FAO (http://fao.org/nr/gaez/en/). They have prepared thousands of spatially explicit datasets on climate, hydrology, fertilizer inputs, soils, crop production, levels of irrigation, growing seasons, etc. These extensive and well-documented suites of global datasets, inclusive of 30 years of collected data, are very valuable for assessing the sustainability of current land uses and agricultural production, and provide a state-of-the-art spatially explicit representation of the current global agricultural situation.

www.Quandl.com is an example of a major numerical database of current and historical global datasets on economics, finances, demographics, societies, markets, energy, health, education, etc. It is an open source collaboration that collects global data and time series data from large international organizations like those mentioned above, as well as: central banks (e.g., US Federal Reserve), US bureaus and agencies, non-US statistical agencies, think tanks and academia (e.g., Gapminder, Yale Department of Economics), and the private sector (e.g., BP, the global energy industry), amongst others. However, not all of the gleaned data is spatially explicit and there is thus a limit to the applicability to some of the datasets.

Another interesting agricultural database is the World Overview of Conservation Approaches and Technologies (WOCAT) database (www.wocat.org). It is an open access database of SLM practices, with a platform to register various sustainability projects. It was developed in conjunction with the Land Degradation Assessment in Drylands (LADA) Project from FAO. The collection is based on extensive questionnaires that detail the perceived benefits of the project by participants and experts. The database is divided into a separate technology database and an approach database. There is also a mapping database, as well as elective modules if the project has climate change or watershed management angle to it. Collectively, there is a lot of information on sustainable management technologies and practices on farms at the local scale, from more than 30 regional or national initiatives. This also includes records for 470 technology and 235 approaches for the sustainability of land management.

The mapping database has a collection of conservation approaches and land use maps developed by the DESIRE project (Wageningen University) for the participating pilot countries. The quality of the individual projects, or at least the reporting, is varied. Specifically, there is a lack of quantifiable information of the effects of SLM on ecosystem services, and some projects lack specific spatial information. Nevertheless, the WOCAT database could potentially be very valuable for identifying cases and technique studies. It can further act as an alternative livelihood information bank, and provides an opportunity to incorporate WOCAT case studies into the ELD Initiative and thus increase information available to both. Finally, there is not a lot of information about the external impacts of WOCAT projects, which is something the ELD Initiative could provide.

The Global Restoration Network (GRN) also hosts a database of hundreds of case studies of ecological restoration projects and initiatives from all over the world (http://globalrestorationnetwork.org/database). This is a collaboration between the IUCN and the Society for Ecological Restoration, to collect information about restoration projects and methods globally. Besides having a case study database, it also includes an extensive library of literature on restoration, with more than 600 references, 150 experts, and information available for main organizations in the field. These latter entries are not up to date but still have valuable information about land restoration and alternative livelihoods. This database is also based on self-reporting and thus has the same restrictions as WOCAT.

The Need for Better Land Use Classification Systems

Land uses are the anthropogenic practices within an ecosystem, *land management* is the method of cultivation, and *livelihood options* are an expression of the different income potential the land holds. Changes in land use are one of the leading drivers of global change, and include land degradation as well as restoration, whether natural land conversions or changes in management forms or livelihoods (Cihlar and Jansen 2001, Foley et al. 2005, Acevedo 2011, Lautenbach et al. 2011, Monteiro et al. 2011, Polasky et al. 2011, Bahadur 2012). Land cover datasets are primary inputs for assessing human, built, and natural capital. They can be augmented with other information such as valuations of ecosystem services, global representations of net primary productivity derived from satellite imagery, and characterizations of ecosystem health and function. Land cover data and maps are readily available but land use data is harder to establish because of the multiple uses for land that could occur within a given land cover.

Land classification is essential to understand, communicate, and compare spatial data. For instance, a land use type classification system was developed for the WOCAT/LADA/DESIRE projects, but each of the land use maps displayed used separate classification systems, and making it difficult to compare between regions. This demonstrates how current classification systems need to be expanded or redesigned to express the multiple uses often associated with actual land use. It is a well-known problem that spatially aggregated measures of geographic attributes tend to conceal local patterns of heterogeneity. This applies to ecosystem services and thus also land use mapping (Troy and Wilson 2006). Thus, the availability of these datasets in time series is crucial to be able to detect changes. At the global level, the world 'next year' looks a lot like it did 'last year'; however, with spatially explicit datasets important significant local changes can often be easily identified. Time series of these kinds of datasets Used in conjunction with time series of 'event' data such as floods, famines, hurricanes, and civil wars, having time series for these types of datasets will be useful for identifying areas in which effort and resources could be focused.

Land use maps are often based on land cover that is identified through remote sensing techniques. Major events such as deforestation, forest fragmentation, recent slash-and-burn agriculture, major canopy fires, monoculture, hydroelectric dams, and large-scale mining are quite assessable using remote sensing data. However, more subtle land uses and management practices or indicators of changes are not as easily determined. This could include: selective logging, subtle edge-effects, soil carbon loss, small scale mining, non-timber plant harvesting, eco-tourism implementation, expansion of narrow unpaved roads (especially in forests), and species invasion (Herold et al. 2011). In these cases, data will rely on on-the-ground observations, natural historical collections of material, and personal/expert accounts.

Classification systems are an attempt to standardize data so that it can be easily understood and facilitate comparison between scales and temporal changes. There are a number of different classification schemes in use throughout the world. Some of the most common are: the original 1976 Anderson, the NLCD 92 Land Cover Classification Scheme (modified Anderson Level II), and the FAO and United Nations Environment Programme (UNEP) Land Cover Classification System (LCCS 3) Classification.

In 1976, the United States Geological Survey (USGS) developed a uniform national land use and land cover classification systems that worked at multiple scales (national, state, and local). This classification scheme is now known as the Anderson classification system and is widely used because of its flexibility and the freedom for local agencies to extend class levels as needed.

Australia uses the Australian Land Use and Management (ALUM) system (http://data.daff.gov.au/brs/landuse/index.cfm?fa=main.classification) for its land use classification, now in its seventh version. Unlike the Anderson classification, it is based on land use ordered by levels of use and potential impacts. It is limited to six main classes, which are very different from the nine main classes of Anderson Scheme that are primarily based on land cover.

At the international scale, FAO and UNEP have adopted LCCS (now in its third version) because the committee recognized that most classification schemes were single use, independent, and used pre-defined classes (http://www.fao.org/docrep/008/y7220e/y7220e00.htm). LCCS is a dichotomous, modular-hierarchical approach classification concept and is universally applicable. This has been used in earlier efforts to analyze land degradation and land use, such as LADA (http://fao.org/nr/lada). They have currently applied LCCS for approval to become an international standard through the TC 211 technical committee of the International Organization for Standardization (ISO) (http://iso.org; http://glcn.org/ont_1_en.jsp). Clearly, there is an abundant amount of data already available from which trends can be seen. The collective challenge is to distinguish that which is significant from that which is not. The real question is: *Is it possible to envision various realistic and probable scenarios and diligently implement, enforce, and maintain the policies and practices needed to achieve the scenarios collectively decided as most desirable*? The scheme needed for this project is one that can deal with land cover and land use and yet also classify based on ecosystem function (or ecosystem dysfunction, as in the case of land degradation). Understanding the ecosystem function of a given land cover can often not be determined from aerial photographs or satellite imagery alone. The optimal classification scheme for this type of project will need to have inputs from other sources including representations of human, built, and social capital.

Scale is at the center of the land use classification problematic. A classification scheme needs to be able to be aggregated up from subcategories to more general categories, as in the CICES protocol mentioned earlier (Haines-Young and Potschin 2012, Maes et al. 2013). For example, in an urban environment at a fine spatial resolution, 'commercial', 'transportation', and 'residential' often get aggregated to an 'urban' classification with coarser spatial resolution. In the same way, 'ponds', windbreaks of trees', and 'row crops' can be aggregated to an 'agriculture' classification. The enormous quantity of satellite data at multiple spatial resolutions suggests there are 'theoretical' data available at all scales all the time. These scales (or resolutions) vary from sub-meter to kilometers and serve different needs. However, there are times when one needs to compare and utilize different resolutions (i.e., to solve problems), and the classification scheme needs to account for this reality. Further complications arise with confusion over land use versus land cover, which may have very different economics and ecosystem service values, i.e., pasture which appears as grassland.

Furthermore, efforts to assess land degradation should not be limited to livelihoods based on the terrestrial surface, but should also include freshwater and marine sources of livelihood diversification. The state of aquatic ecosystem services can be a source of increased or decreased pressure on land conditions. If land is heavily degraded, people might seek out aquatic sources to increase income and well-being. Conversely, if the aquatic ecosystem is depleted, it might increase the pressure on the land (Granek et al. 2010a, Luisetti et al. 2011) and ultimately on the level of degradation. Examples of ecosystem services that stem from water-based systems include storm protection, hatcheries, fisheries, coral reef biodiversity, ecotourism, and many others (Costanza et al. 2008, Barbier et al. 2011, Gedan et al. 2011). There are very few management plans that include both the aquatic (especially marine) and terrestrial ecosystems, even though they are highly interconnected. These are some of the viable alternative livelihoods that should be identified as part of the ELD Initiative, as also stated in the ELD Scientific Interim Report (Francour et al. 2001, Barbier et al. 2011).

Valuation Methods for Natural Capital and Ecosystem Services

Once interrelated ecosystem services have been identified, quantified, and mapped, several techniques are available for a TEV. Since ecosystem services are the benefits that people derive from ecosystems, that is - the support of sustainable human well-being that ecosystems provide (Costanza et al. 1997, MEA 2005) - the value of ecosystem services is the relative contribution of ecosystems to that goal (Figure 1). There are multiple ways to assess this contribution (see Box 1), some of which are based on an individual's perceptions of derived benefits. These methods can be divided into 'revealed preference' or 'stated preference'. Revealed preference methods use market prices as a proxy for benefits. Of course, this approach only works for goods and services that are traded in markets, but only a small subset of ecosystem services (some provisioning services) are traded in markets. Stated preference methods attempt to construct 'pseudo markets' via surveys that ask people to state their willingness to pay for ecosystem services not traded in markets. These include various versions of contingent valuation and choice modelling (ELD Initiative 2013, p33, fig 4).

However, stated preference approaches have severe limitations when applied to ecosystem services (Liu and Stern 2008). Individuals have imperfect information about ecosystems and their connections to human well-being, as well as discomfort with stating trade-offs for ecosystems in monetary units. Since individual perceptions are limited and often biased

(Kahneman 2011), it should be incorporated and accounted for in the ELD Initiative valuation method to avoid inaccuracies.

Conventional economic valuation

Revealed-preference approaches

Travel cost: Valuations of site-based amenities are implied by the costs people incur to enjoy them (e.g., cleaner recreational lakes).

Market methods: Valuations are directly obtained from what people must be willing to pay for the service or good (e.g., timber harvest).

Hedonic methods: The value of a service is implied by what people will be willing to pay for the service through purchases in related markets, such as housing markets (e.g., open-space amenities).

Production approaches: Service values are assigned from the impacts of those services on economic outputs (e.g., increased shrimp yields from increased area of wetlands).

Stated-preference approaches

Contingent valuation: People are directly asked their willingness to pay or accept compensation for some change in ecological service (e.g., willingness to pay for cleaner air).

Conjoint analysis: People are asked to choose or rank different service scenarios or ecological conditions that differ in the mix of those conditions (e.g., choosing between wetlands scenarios with differing levels of flood protection and fishery yields).

Cost-based approaches

Replacement cost: The loss of a natural system service is evaluated in terms of what it would cost to replace that service (e.g., tertiary treatment values of wetlands if the cost of replacement is less than the value society places on tertiary treatment).

Avoidance cost: A service is valued on the basis of costs avoided, or of the extent to which it allows the avoidance of costly averting behaviors, including mitigation (e.g., clean water reduces costly incidents of diarrhea).

Non-monetizing valuation or assessment

Individual index-based methods, including rating or ranking choice models, expert opinion.

Group-based methods, including voting mechanisms, focus groups, citizen juries, and stakeholder analysis.

Box 1 (adapted from Farber et al. 2006)

Respondent bias is an on-going challenge in ecosystem services valuation, but some of the existing valuation methods like avoided and replacement cost estimates are not dependent on individual perceptions of value. For instance, in choice experiments, individuals are asked to rank alternative scenario outcomes, which seems to be an easier way for people to think about trade-offs (Farber et al. 2002). The degree of replication needed to produce an estimate of value is achieved by sending different versions of the scenario-ranking questionnaire to a number of participants.

Table 2 shows the relationship between valuation methods and the ecosystem services they are most appropriately applied to. Note that there is generally not one correct approach, but a range of approaches that should be used and compared.

Table 2. *Categories of ecosystem services and appropriate methods of valuation (adapted from (Farber et al. 2006))*

Ecosystem services	**Amenability to economic valuation**	**Most appropriate method for valuation**	**Transferability across sites**
Gas regulation	Medium	CV, AC, RC	High
Climate regulation	Low	CV	High
Disturbance regulation	High	AC	Medium
Biological regulation	Medium	AC, P	High
Water regulation	High	M, AC, RC, H, P, CV	Medium
Soil retention	Medium	AC, RC, H	Medium
Waste regulation	High	RC, AC, CV	Medium to high
Nutrient regulation	Medium	AC, CV	Medium
Water supply	High	AC, RC, M, TC	Medium
Food	High	M, P	High
Raw materials	High	M, P	High
Genetic resources	Low	M, AC	Low
Medicinal resources	High	AC, RC, P	High
Ornamental resources	High	AC, RC, H	Medium
Recreation	High	TC, CV, ranking	Low
Aesthetics	High	H, CV, TC, ranking	Low
Science and education	Low	Ranking	High
Spiritual and historic	Low	CV, ranking	Low

AC=avoided cost, CV=contingent valuation, H=hedonic pricing, M=market pricing, P=production approach. RC=replacement cost, TC=travel cost

Aggregation and scaling

Ecosystem services are often assessed and valued at specific sites for specific services. However some uses require aggregate values over larger spatial and temporal scales (Table 3). Producing such aggregates suffers from many of the same problems as producing any aggregate estimate, including macroeconomic ones like GDP.

Table 3. Four levels of ecosystem service value aggregation (Croen et al. 1991)

Aggregation method	Assumptions/approach	Examples
1. Basic value transfer -	assumes values constant over ecosystem types	(Creasy 1993, Costanza et al. 2002))
2. Expert modified value transfer	adjusts values for local ecosystem conditions using expert opinion surveys	(Batker et al. 2010)
3. Statistical value transfer	builds statistical model of spatial and other dependencies	(de Groot et al. 2012)
4. Spatially Explicit Functional Modeling	Builds spatially explicit statistical or dynamic systems models incorporating valuation	(Boumans et al. 2002, Costanza et al. 2008, Nelson et al. 2009)

Most aggregates are ‘accounting measures’ of the quantity of ecosystem services (Howarth and Farber 2002). In this accounting dimension the measure is based on virtual non-market prices and incomes, not real prices and incomes. This degree of approximation is appropriate for some uses (Table 3), but ultimately a more spatially explicit and dynamic approach would be preferable and more accurate for scaling up. Regional aggregates (e.g., watershed or provinces such as EEA’s NUTS 3 levels) are useful for decision-makers to assess land use change scenarios. National aggregates are useful for revising national income accounts. Global aggregates are useful for raising awareness and triggering action by emphasizing the importance of ecosystem services relative to other contributors to human well-being.

Modelling at a scale appropriate for land management (e.g., farm scales) provides important information about choices and decision-making. Different frameworks can be based on data availability and adapted by different schools, groups, and disciplines (cf. (Boyd and Banzhaf 2007, Carpenter et al. 2009, Fisher et al. 2009, Sukhdev and Kumar 2010, Seppelt et al. 2011, Seppelt et al. 2012)). These models can then be aggregated and scaled up to cover whole landscapes, and regional, national and global levels. While there has been a call for a standardized ecosystem service accounting unit and framework that allows for transparent aggregation between scales and disciplines (Boyd and Banzhaf 2007, Costanza 2008, Lamarque et al. 2011), it is clear that no one valuation framework will work for all purposes (Costanza 2008).

Drivers of Land Degradation

Understanding the drivers of land degradation is one of the major knowledge gaps identified by the ELD Scientific Interim Report (ELD Initiative 2013, p61, box 9, no. 2), as well as assessing the impact of the pressures and patterns of degradation in Step 5 of the 6+1. The drivers of degradation are many and complex, resulting from a range of different interactions over time and space (Figure 6) and each case is distinct (Verburg et al. 2002, Geist and Lambin 2004). They include both proximate drivers such as topography, land cover and vegetation, soil resilience, climate, and poor management, and underlying drivers such as poverty, decentralization, access to agricultural extension services, land cover changes, and commodity market access (Lambin et al. 2001b, Geist and Lambin 2004, Andersson et al. 2011, Von Braun et al. 2013). Indicators of these biophysical, social, and economic types of drivers are important in identifying what the cause of the degradation is and which alternative scenarios will be part of the cost-benefit analysis (CBA). They include, *inter alia*, climate conditions, biodiversity, measures of vegetation density, soil properties, topography, land management practices, land tenure, population density, road density, administrative borders, national policies, institutions, socioeconomic indicators, access to information, and farmer perceptions.

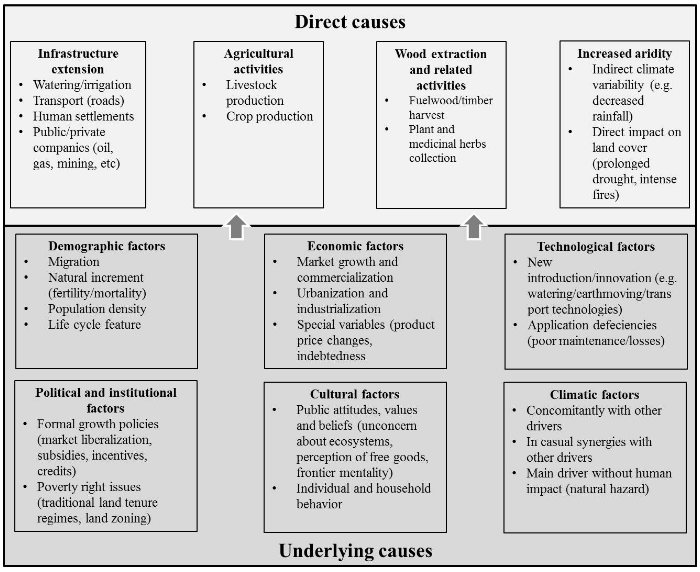


Figure 6. Drivers of Land Desertification (Geist and Lambin 2004)

Not surprisingly, agriculture is one of the major proximate drivers of land degradation, although the amount of degradation is amplified by co-occurrence of the other types of drivers, e.g., increased aridity (Geist and Lambin 2004). Natural processes such as weather variability and extremes increases the need for adaptive management and land restoration processes. If this is not present, the combination of highly variable rainfall and lack of adaptive management causes high degrees of land degradation (McIntyre and Tongway 2005, Stafford Smith et al. 2007). For instance, in Australia, agricultural and pastoral processes that increase the proportion of annual plants can cause soil degradation, acidification, salinity, erosion, etc. (Bolan et al. 1991, Dalal et al. 1991, Randall et al. 1997, Scott et al. 2000, Sumner and Noble 2003, Tongway et al. 2003, Brennan et al. 2004, Dunlop et al. 2004, Bouwman et al. 2005, Lavelle 2005, Glover 2010, Bell et al. 2013, Pingali 2013). It is evident in many places that agriculture is increasingly becoming locked-in to conventional, high input, intensive management systems through genetic changes of plants and animals. It is widely acknowledged that fertilizers, pesticides and herbicides generate significant damage to above and below ground biodiversity and negatively affect soil fertility and structure. Modern development of plants and animals involves selective breeding in high input environments and as a result produces plant and animal genetics that are optimized for high input systems and which fail to perform in low input systems. In these management systems, the lack of acknowledgement of ecosystem services and successful payment schemes restrain investment in such ideas (Van Der Ploeg et al. 2006, Swinton et al. 2007, Wossink and Swinton 2007, Jack et al. 2008, Vanloqueren and Baret 2009, Stallman 2011).

In addition to the aforementioned sources and databases, data from the LADA and DESERTLINKS projects' DIS4ME Database has extensive information available on degradation patterns. The DIS4ME Database has collected 150 sets of indicators from projects. The analyses include land use classification and mapping, as well as a global Normalized Difference Vegetation Index (NDVI) study (GLADA) by the International Soil Reference and Information Centre (ISRIC). Additionally, a set of pressures and threats indicators was mapped at the global level. The information is accessible at country and pixel (5 arc-minute resolution) levels in the Global Land Degradation Information System (GLADIS) database in DIS4ME. Kosmas et al. (2013) established the risk of desertification and the significant indicators in drylands from 17 different study sites from the DESIRE and MEDALUS projects (http://desire-his.eu). This study resulted in a reduction in the effective number of indicators to measure degradation from land use. The main indicators were agriculture, pasture, forest; and degradation type water erosion, tillage erosion, soil erosion, water stress, overgrazing, and forest fires.

Drivers of management decisions are equally as complex, highly varied and dynamic (Lambin et al. 2001a, Douglas 2006), and indicators need to be informed with knowledge, opportunity, and motivation (Kosmas et al. 2013, Shepherd et al. 2013). Knowledge and motivation are important for setting and achieving land condition goals driven by the economy, e.g., private returns from trading private and public goods (Stafford Smith 1994, Kwansoo et al. 2001, Kroeger and Casey 2007, Stafford Smith et al. 2007). The ability to import otherwise limited resources such as fertilizers, or export sustainability issues, e.g., timber collection, can disguise natural constraints and thus degradation (Nakicenovic et al. 2000, Geist and Lambin 2004, Oleson 2011). The OECD and EEA have developed a database (http://www2.oecd.org/ecoinst/queries/Default.aspx) that lists different public and voluntary instruments and monetary incentives for environmental policies, such as subsidies, taxes, rebates, and refund mechanisms for all the member states in EU and OECD. This can help identify the knowledge gaps (ELD Initiative 2013, p61, box 9, no. 12-14) that surround policies on SLM, and identify which policy measures are appropriate and available for a certain region or approach.

ELD and other existing methods

What makes the ELD an interesting initiative for this age-old problem of promoting SLM? There are other significant efforts to assess the extent of land degradation across different case study sites and for different ecosystem types (ELD-Initiative 2013). For instance, Nkonya et al. (2013) deals with a similar approach as the ELD Initiative, i.e., they are both founded on the TEV. Additionally, both Nkonya et al. (2013) and the ELD Initiative are mapping global land degradation and modelling the impacts of land management decisions on the level of degradation, however there are significant differences. Nkonya et al. (2013) relies mostly on use values in their case study assessments, whereas the ELD aims for a more comprehensive valuation process that engages spatially explicit models for valuation of ecosystem services and other capital stocks and flows.

This approach gives a more accurate and reliable output, e.g., for spatial aggregation and accurate accounting. Furthermore, Nkonya et al. (2013) use the comparison of cost of action of adopting SLM practices versus the inaction of business-as-usual, to analyze the most beneficial approach to land management. Not all approaches to ecological restoration will result in 100 per cent functional land, which might very well be impossible to regain. If that is the case, the cost of inaction will overestimate the benefit from action (see ELD Initiative, p34, fig 5).

On the other hand, the ELD Initiative goes beyond what has been done already. The main goal is determining the economic costs of action versus benefit of action, and comparing these cost and benefits for multiple livelihoods options, land values, and the impact on overall human well-being (ELD-Initiative 2013, Nkonya et al. 2013). The 6+1 methodology and the net economic benefit decision-making framework (ELD Initiative, p39, fig 7) makes comparisons between different scenarios and land use options transparent and intuitive for decision-making (ELD-Initiative 2013) and thus also improves the applicability of the methodology in both theory and practice. It does, however, mean the caveats and the knowledge gaps identified by the Interim Report have to first be overcome (ELD Initiative, p61, box 97).

Modeling

Even though the ELD methodology is very well structured, there are still a few problems in the 6+1 step methodology, as highlighted in the Scientific Interim Report (ELD Initiative 2013, p61, box 9). The heterogeneity of spatial and temporal scale highlights the complexity of the human–nature interactions (Costanza et al. 2002, Costanza and Voinov 2003, Aertsen et al. 2012, Dale et al. 2013). Additionally, the analyses are further complicated with matters like the lack of a harmonized methodology to conduct environmental valuations, as discussed above.

The heterogeneity of spatial and temporal scale highlights the complexity of the human–nature interactions (Costanza et al. 2002, Costanza and Voinov 2003, Aertsen et al. 2012, Dale et al. 2013), and matters like the lack of harmonized methodology to conduct an environmental evaluation, as discussed above, complicates the analyses and this is important to acknowledge and prioritize.

The following summarizes selected and widely used mathematical models available for different systems and scales. They operate on temporal and spatial scales that could be used for studies of local, national, or global systems or part of systems, depending on the level of detail they can handle. The models have been selected to represent tested and widely used models that could serve as a toolbox for researchers that look into sustainable land management studies, and has been divided into sections by the level of spatial aggregation and integration of a wider amount of the capitals. As mentioned above, different scales of analyses are useful for different objectives, whether that is for local or global processes and stakeholder representations. Some examples at the larger scale, include Dynamic Global Vegetation Models (DGVM) while at smaller scales (regional, farm and site scale) include process based and simulation models. Figure 3 show an overview of the models selected.

Farm and Site Scale Models

CropSyst: (http://modeling.bsyse.wsu.edu/CS_Suite/)) operates on a very small scale, square meters. The model is a simulation model with outputs of management actions on multiple crops with daily time series. The model simulates the soil water budget, soil-plant nitrogen budget, vegetation growth, dry matter production, yield, and erosion, among others (Stöckle et al. 2003). The model was developed as an analytic tool to analyze the effect of management on both the productivity and the environment. Management options are cultivar selection, crop rotation (including fallows), irrigation, nitrogen fertilization, tillage (over 80 options), and green residue management. Moreover, it links to GIS software and a weather generator. It also links to economic and risk analysis models, although these are still under development. CropSyst has been applied to several crops (corn, wheat, barley, soybean, sorghum, and lupines) and regions (Western US, Southern France, Northern and Southern Italy, Northern Syria, Northern Spain, and Western Australia).

DNDC: DeNitrification-DeComposition (http://www.dndc.sr.unh.edu/) is a computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems that operates on the scale of plot to field. It is a process-based model that simultaneously models agricultural trace gas emissions, soil C sequestration, and crop yield.
The model predicts crop growth, temperature and moisture of the soil, soil carbon dynamics, nitrogen leaching, and specifically emissions of trace gases including nitrous oxide (N_2O), nitric oxide (NO), dinitrogen (N_2), ammonia (NH_3), methane (CH_4) and carbon dioxide (CO_2). The model is comprised of three sub models: thermal-hydraulic, decomposition, and denitrification. Simple climate data drive the model, and thus produce dynamic soil profiles of temperature and moisture, and changes in aerobic-anaerobic conditions. Additional data sources are texture and biochemical properties, and agricultural practices. Daily N_2O and N_2 emissions are calculated during rainfall events and emissions of these gases are predicted by counting nitrification N_2O emissions into the calculations. After strict sensitivity simulation, it was shown that variations in temperature and precipitation, organic carbon and clay content, as well as pH had significant effects on denitrification rates and nitrous oxide emissions. The responses of DNDC are consistent with field and experimental results reported in the literature. The downside of this model is that because of its small-scale complexity a very data hungry model and it needs calibration wherever used. Since the model was originally developed for cropping systems, various variants of the model has been adapted to different ecosystems and regions (Giltrap et al. 2010).

APSIM: Agricultural Production Systems sIMulator (www.apsim.info) is an agro-ecosystem process based model, on field to farm scale. It was developed to simulate biophysical processes in agricultural systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk. The model has been used for many different applications including: on-farm decision making support, production or resource management on-farm, analysis of supply chain issues in agricultural business setups, waste management guidelines, and risk assessments.
APSIM consists of three different modules: plant, soil and management. Each of them include a diverse range of crops, pastures and tree production, soil processes, as well as water balance, N and P transformations, soil properties, erosion and a large range of management settings. APSIM was developed because of a need for tools to accurately predict crop

production and its correlations to climate, genotype, soil, and management factors of sustainable long-term resource management. Unfortunately, the impacts of management on soil physical structure are not included in the model. Furthermore, the dynamics of phosphorus are poorly modeled, and the impact of management on soil C and of soil physical structure on root growth are still being developed (Wang et al. 2009).

CENTURY: (http://www.nrel.colostate.edu/projects/century/) this model simulates macro nutrient dynamics, on both farm and field scale. The temporal units are monthly time steps for an annual cycle over centuries and millennia. It embodies the best understanding of the biogeochemistry of C, N, P, and S, available today. Agricultural production can be simulated by using presets of grassland/crop, forest or savanna system sub-models, with possibilities of specifying potential primary production of site-specific plant communities. Land use change is represented by changing the structure of the plant community types in the runs. CENTURY was developed to analyze the cropping system rotations and tillage practices, for a holistic systems analysis of the effects of land management, CO_2 fertilization, and climate change on the efficiency and sustainability of agroecosystems(Kirschbaum et al. 2001). The model has incorporated the effects of climate, soil variables and management to simulate C, N, and hydrology in the soil-plant system. It is possible to run complex simulations of agricultural management systems, such as crop rotations, tillage practices, irrigation, grazing, harvest methods, etc. (Kirschbaum et al. 2001). For testing land degradation effects on small scale, the Century model has potential. It has a high ability to model a diverse array of ecosystems, and can simulate a wide range of disturbance events, relevant for analyses of land use, land use change and forestry. It has also been extensively used and tested around the world on multiple systems.

Nevertheless, the model is largely empirical and the high number of parameters can seem overkill because only a few can be selected. Furthermore, the plant production model sub is a little too simple for an accurate output compared to those of specialist models. This model was developed to provide a tool for ecosystem analysis, and excels in evaluating the effects of changes in management and climate on ecosystems.

DAYCENT:(http://www.nrel.colostate.edu/projects/daycent/index.html) is the daily time-step version of the CENTURY biogeochemical model (Parton et al. 1994). DAYCENT simulates fluxes of C and N among the atmosphere, vegetation, and soil. Recent improvements to the model include the ability to schedule management events daily and the option of making crop germination a function of soil temperature and harvest date a function of accumulated growing degree-days. The ability of DAYCENT to simulate NPP, soil organic carbon, N_2O emissions, and NO_3 leaching has been tested with data from various native and managed systems (Del Grosso et al. 2001, Del Grosso et al. 2002, Del Grosso et al. 2005).

EPIC: Environmental Policy Integrated Climate (http://epicapex.tamu.edu/epic/) is a cropping systems model that estimates soil productivity when it is stressed by erosion. EPIC simulates more than eighty crops per crop growth model, by using distinct parameter values for each crop. It also predicts the effects of management decisions on soil, water, nutrient and pesticide movements. Their combined impact on crop yields, soil loss, and water quality for areas with comparable soils and management decisions are also measurable. The model has a wide range of useful outputs, for instance the difference in erosion class soils, types of erosion losses, as well as their impacts on crop productivity. Furthermore, it estimates the effects of nutrient treatments, phosphorous and nitrogen leaching and surface runoff , from fertilizer, manure, and pesticide applications. Lastly, the model shows great potential in analyzing the effects of climate change and drought impacts on crop yield and erosion and identifies effective management that sequesters carbon in the soil, which could be an important measure in restoring degraded land. Another feature that has special interest for analyses of sustainable land management is the fact that the EPIC model estimates the effect of management systems on sediment and nutrient losses, as well as an economic-environmental analyses in response to alternative cropping systems, management practices, and other scenarios, which could prove important for an analysis of the costs of land degradation.

Watershed and Regional Scale Models

APEX: Agricultural Policy/Environmental eXtender Model (http://epicapex.tamu.edu/epic/) is a landscape scale model from the same developers as EPIC, and it deals with watershed scale analyses. APEX has modules for routing water, sediment, nutrients, and pesticides, through complex landscapes that make up the watershed, as well as groundwater and reservoir components. APEX was developed to evaluate a range of land management strategies and take into consideration sustainability, erosion, economics, water supply and quality, soil state, plant community competition, weather, and pests. The watershed can be sectioned into homogenous areas to assure that each area is relatively identical in terms of soil, land use, management, and weather. The interesting feature of the APEX model is that it is one of the most comprehensive model available in current landscape-scale models and analyses of subareas and channel systems can be simulated within the model.

DSSAT: Decision Support System for Agrotechnology Transfer (www.dssat.net) is a cropping system model (CSM) software application program, which can run on farm to regional scale. It was originally an on-farm model developed handle precision management, with a component to analyze regional assessments of climate variability and climate change impacts. The DSSAT has simulation models for more than 28 crops, and has been used for more than 20 years by researchers, consultants, managers, policy and decision makers worldwide, and thus is well known and understood by stakeholders. Unfortunately, it only deals with crops and therefore is quite simple in its output. Furthermore, it does include a pest module but this performs poorly at the local scale and underachieves with soil constraints in field conditions.

STICS: Simulateur mulTIdiscplinaire pour les Cultures Standard (http://www.inra.fr/en/Scientists-Students/Agricultural-systems/All-reports/Modelling-and-agrosystems/STICS-an-agronomy-dynamo/(key)/0). The model can analyze inputs of climate, soil and the cropping system, from plot to regional scale. STICS calculates the properties of the agricultural output, e.g. crop yields, harvest quality, and plant nitrogen. Furthermore, STICS is also able to assess environmental impacts, such as nitrate leaching and greenhouse gas emissions. The model was developed to upscale experiments to study the effects of climate change and the impact of secondary cover crops for nutrients trapping. The model is calibrated for 24 perennial and annual crops. Unfortunately, some processes, e.g. ammonia volatilization, drought resistance, are not included in the model and thus the use is limited to a restricted number of cropping systems.

LPJmL: The Lund-Potsdam-Jena managed Land model (http://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml/how-tos) is a global dynamic vegetation model (DGVM). The LPJmL model is designed to simulate the terrestrial carbon cycle and the effect on vegetation patterns under climate change, globally. It was quickly extended to simulate the terrestrial water cycle as well, because the carbon and water

cycles are closely linked. Using a combination of plant physiological relations, functions and plant traits as the parameters, the model simulates a multitude of processes such as photosynthesis, fire disturbance, soil moisture, runoff, irrigation, and vegetation structure, among others, for both natural and agricultural ecosystems.
LPJmL is the only DGVM with a dynamic land use component integrated at the global scale. Also, it simulates the woody and herbaceous bioenergy producing plantations. The input data are spatially explicit time series (~60,000 global 0.5x0.5° grid cells) and consists of climate, human land use, soil properties, and river flow directions. Grid cells can consist of mosaics of one or more types of natural or agricultural vegetation cover. Daily, monthly or annual outputs comes with spatially explicit time series for distinct plants, carbon, and water pools and fluxes, specific land-use types or a collection of the entire mosaic per grid cell. It includes 10 plant functional types and 13 crop functional types, used to model forest and agricultural uses, including crops, grazed grasslands, as well as irrigation options.

ORCHIDEE (http://labex.ipsl.fr/orchidee/) can analyze local scale (km) to global scale (0.5 degree) depending on the spatial resolution of input data. The ORCHIDEE DGVM is part of the IPSL Earth System Model for the 5th IPCC report as the terrestrial component (Krinner et al. 2005). ORCHIDEE was developed to represent both natural ecosystem and human managed carbon, water, and energy dynamics from site to globe scale on sub-daily to centennial scales (Krinner et al. 2005).
The ORCHIDEE model has carbon, water and energy fluxes on a 30 minutes to annual frequency as the main outputs. Furthermore, vegetation distribution (using the plant functional type approach), and carbon stocks are also simulated. To run ORCHIDEE, sub-daily to monthly climate inputs for a large amount of process types, such as carbon stocks and vegetation distribution, features of managed ecosystems and disturbance .

Biome-BGC (http://www.ntsg.umt.edu/project/biome-bgc) differs from LPJmL since it estimates fluxes and storage of energy, water, carbon, and nitrogen for the vegetation and soil components. The output is conveniently daily fluxes, but the model is very weather data hungry, which can be a limitation in certain areas.

CARAIB: The CARbon Assimilation In the Biosphere, is a mechanistic DGVM model of carbon assimilation in the biosphere estimates the net primary productivity (NPP) of the continental vegetation on a grid of 1° × 1° in latitude and longitude. The model considers the annual and diurnal cycles. It is based on the coupling of the three following sub models; a leaf assimilation model including estimates of stomatal conductance and leaf respiration, a canopy model describing principally the radiative transfer through the foliage, and a wood respiration model. This calculates the influence of the seasonal and inter-annual climate changes on the carbon fluxes between continental biosphere and atmosphere, with monthly averages as output, but does not have a soil data component.

Integrated Global Models

An option is that could avoid some of the identified difficulties and shortcomings is to adopt a holistic approach by creating a ‘whole-systems’ perspective model. This would also avoid treating the system as an additive series of disaggregated components (Dale et al. 2013). Adopting spatially explicit models to improve the shortcomings of current ecosystem services valuations and provide a broader estimation of human well-being will give a better reference point for the real global problem of land degradation than previous collective analyses. Such a model would need to address the complexity and connectedness from the field or farm scale to national and global scale economies. Suitable spatial and temporal modules need to be established to reduce the variability and increase the comparability between different management options.

Integrated global models (IGMs) attempt to build quantitative understanding of the complex, dynamic history and future of human–environment interactions at the global scale, and are thus more comprehensive than both the process-based and simulation based models. There is now a 30-year history of this approach. Over this period, computer simulation modeling has become a well-accepted technique in scientific analysis, but truly integrated simulation models—those that deal with the dynamics of both the natural and human components of the system and their interactions—are still relatively rare, and those that do this at the global scale are even rarer. Below are some of the major examples.

World3: is a globally aggregated systems dynamics model broken into five sectors: population, capital, agriculture, nonrenewable resources, and persistent pollution and containing 16 state variables (i.e., population, capital, pollution, and arable land), 100 variables total and 80 fixed parameters (Meadows et al. 1974). The latest versions are written in STELLA and are easy to run on a PC; however, they are not freely available to the public.

World3 has been criticized on methodological grounds (e.g., (Cole et al. 1973)). The most often cited difficulties are that it does not include prices explicitly, that it *assumes* resources are ultimately limited, and that it does not present estimates of the statistical uncertainty on its parameters. In fact, World3 is a viable and effective method to reveal the implications of the primary assumptions about the nature of the world that went into it. That is all that can be claimed for *any* model. These assumptions or "pre-analytic visions," need to be made clear and placed in direct comparison with the corresponding assumptions of the alternatives, in this case the "unlimited growth model." The essential difference in pre-analytic visions centers on the existence and role of limits: thermodynamic limits, natural resource limits, pollution absorption etc. The alternative unlimited growth model, derived from neo-classical economic theory (see, e.g., the DICE model below), *assumes there are no limits* that cannot be overcome by continued technological progress, while the limited growth model *assumes that there are limits,* based on thermodynamic first principles and observations of natural ecosystems. (Meadows et al. 1992, Meadows et al. 2004).

While the discussions of World3 often point to the limited vs. unlimited growth assumptions as a key difference with conventional economic models, they do not take the opportunity to look at the relative costs and benefits of being right or wrong in those assumptions. If one does this, one can easily see that the cost of assuming no limits and being wrong is the collapse scenarios shown by World3, while the cost of assuming limits and being wrong is only mildly constrained growth (Costanza et al. 2000). Some of the more recent models reviewed below try to elaborate on these scenarios, World3 is also probably the only IGM for which a true "validation" test could be run based on historical datasets. Recently, Graham Turner took the original forecasts made in 1972 of the period from 1972 to 2000 and compared them with the actual data from the 1970–2000 period (Turner 2008). This showed that the World3 model was very accurate in its predictions, using the "standard run" or "business as usual" scenario, which does not show collapse until the middle of the 21st century.

Because of the influence of the original book (several million copies were sold), this model has been the topic of intense scrutiny, debate, misunderstanding, and, one could argue, willful misinformation over the years. One interesting bit of misinformation that has been persistently circulating is the idea that the model's "predictions" have been proven totally wrong by subsequent events (Economist 1997). In fact, the model's forecasts made in 1972 have been pretty much on target so far. In an interview with the Dutch *Volkskrant* (April 16, 2005), Meadows compares his "1972" scenarios with the outcome of the Millennium Ecosystem Assessment (Reid et al. 2005) and states that this assessment actually confirms the scenarios. See also Turner (2008) who assesses the performance of World3 from 1970-2000. The model's forecasts of collapse under certain scenarios did not start to occur until well past the year 2000. The true tests of this model's forecasts will arrive in the coming decades or so.

At the time of its initial release in 1972, World3 was at the cutting edge of computer simulation. Since then, simulation capabilities have increased dramatically, as has the availability of data to calibrate and test global models. The remaining models in this review show some of that development. Before leaving this brief discussion of World3, however, we should mention some of the things that could have been done, especially in the recently released 30-year update, but have not been. The most important of these has to do with calibration and testing. In all the books on World3, calibration of the model with historical data is downplayed. This is strange, since the model runs always start in 1900 and run for 200 years to 2100. Why not show historical data for the variables in the model for which historical data is available in order to demonstrate the model's "skill" at reproducing the past? The reason given for this is that since the model is only an approximation, one should not put too much emphasis on "precise" calibrations. We think this is ultimately a mistake, since it misses the opportunity to present quantitative tests of the model's performance — tests against which World3 would fare quite well and which would address at least some of the objections of its critics.

IMAGE (Integrated Model to Assess the Greenhouse Effect; (Rotmans 1990)) aims to create a comprehensive overview of global climate change. IMAGE was one of the first models that implemented OECD's Driver-Pressure-State-Impact-Response (DPSIR) approach (InterFutures Study Team 1979) into a global model by integrating a series of different models for each important subcomponent. It simulated the emissions from energy use and tropical deforestation and the consequent climate change in different regions. A few feedback processes, such as CO_2 fertilization, were included mainly to calibrate the model to simulate observed atmospheric CO_2 concentrations. The only impact that was simulated was sea level rise and its consequences for the Netherlands. One of the conclusions, for example, was that the costs to deal with sea-level rise would amount to more than half a percent of the Dutch national product. Most of the model components simulated the physical system (oceans, atmosphere and C on land). Societal aspects were not strongly included. They determined emission levels, and defined the cost of impacts.

The extended version IMAGE-2 (Integrated Model to Assess the Global Environment; (Alcamo et al. 1998)) is a further development of IMAGE. The model was initially developed to link important scientific and policy aspects of climate change in a geographically explicit manner in order to assist decision making (Alcamo 1998). Major emphasis was put on incorporating different components of the earth system, including oceans, biosphere, atmosphere and anthroposphere (i.e., society) and all major interactions and feedbacks. Over the years the model has been developed further by incorporating more detail (e.g., water use and land degradation) and improved underlying datasets. The IMAGE 2.2 version has been used intensively for supporting science-policy dialogues, which led to, for example, the so-called safe landing approaches (Alcamo and Kreileman 1996) and the scenario developments of IPCC (i.e., SRES; (Nakicenovic and Swart 2000)), UNEP's Global Environmental Outlook, and the Millennium Ecosystem Assessment. The extensive application of IMAGE-2 is illustrated by the fact that IMAGE-2 has been one of the very few models that has been used by all the different IPCC working groups.

The IMAGE model was developed in the second half of the eighties at the then new Dutch Institute of Public Health and Environmental Protection (RIVM). RIVM strongly advocated such an integrated modeling approach, which led to presentations in Dutch parliament and helped to raise the awareness of Dutch policy makers to climate change. When the IPCC was established, IMAGE became one of the models that helped to scope the earliest IPCC-IS92 scenarios, which defined the input for the climate-change modeling and impact community for over a decade. Also, several mitigation scenarios have been developed and published. Scientifically, IMAGE has been instrumental in the debate on global warming potentials. Because not only CO_2 but all greenhouse gases were included in the model, along with a then state-of-the-art atmospheric chemistry model, the advantages and limitations of this concept could be easily determined.

IMAGE has been systematically scrutinized using sensitivity analysis (Rotmans 1990). As a matter of fact, automated Monte Carlo analysis was first tested on IMAGE, which led to advanced protocols for experimental design for model testing (Kleijnen et al. 1992). Such analysis resulted in the identification of important variables, which have to be determined accurately and less sensitive variables, whose value does not matter so much. This analysis helped to advance the modeling research agenda. But it also showed that variables important to stakeholders rarely were the most sensitive ones, which frustrated the actual agenda setting process. Additionally, meta-modeling was tested for IMAGE. Meta-modeling searches for simpler relationships between model input and output, so that model experiments can be executed much faster. Meta-modeling techniques proved extremely useful in the development of scenarios, especially those for systems whose futures are uncertain. This was especially required in the days when computing was much less powerful. One of the outcomes of the meta-modeling of IMAGE was that besides the expected costs of dike raising, one of the most important factors determining the impacts was the not well-known role of the Antarctic and Greenland ice sheets on sea level rise. This uncertainty is still not resolved in recent IPCC reports.

IMAGE-2 is one of the most advanced integrated assessment models currently available. Its major innovative aspect was (and still is) that it simulates energy and industry related activities simultaneously with land-use activities for the same set of drivers. This creates a much greater consistency for the different scenarios. Additionally, a spatially explicit global land-use model, based on a few transparent rules, creates highly different dynamics and patterns across different continents. This approach was also a major achievement. The model was calibrated against historic atmospheric CO_2 concentrations in order to balance oceanic and terrestrial carbon pools. Historic trends in land use, energy use and industrial activities for the last decades were used to calibrate the socioeconomic models. Data for these trends are derived from large internationally available databases, compiled by institutions such as FAO, UN, International Energy Agency (IEA), and the World Bank. IMAGE-2 now includes models for demography and the world economy to provide more detail and consistency for population (e.g., mortality, fecundity, and age structures) and economic drivers (trade, labor forces, resource use, and other economic constraints). The simulations start in 1995 and run until 2100 with annual time steps. Output of the model is diverse and covers many aspects of the Earth system. Scientific publications have focused on the importance of feedback processes and impacts on ecosystems and agriculture (e.g., (Leemans and Eickhout 2004)). Policy oriented applications have focused on scenarios and climate protection targets (e.g., (Alcamo and Kreileman 1996), see S5). Just this year (2014) the IMAGE 3.0 has been released and models the long-term impacts of global changes from the interaction of demographic, technological, economic, social, cultural and political factors.

The philosophy of the IMAGE-2 group has always been to be scientifically sound in order to be accepted by the policy community that needed scientific advice and/or scenarios. This was achieved by frequently publishing in the international peer-reviewed scientific literature and by installing a scientific advisory board. The strength of IMAGE-2 was therefore its widely available documentation (two books, over 100 papers, and 4 CD-ROMs). IMAGE-2 was especially well accepted by the ecological science community. Scenarios from IMAGE-2 are now widely used by that community. Its weakness is that using the model requires a well-trained multidisciplinary team and that it has proven difficult to communicate transparently the detailed results. Some argued that the presented detail, especially on maps, provided a false impression of precision. IMAGE-2 has consequently often been condemned because too little attention was paid to uncertainty (e.g., (van der Sluijs 1997)). Currently, new methods using aggregated indicators are being developed to communicate results and the inherent uncertainty (e.g., (Leemans and Eickhout 2004)).

True validation of such a model (with such a forward looking objective) and its scenarios is only possible by observing the future. As an alternative, the IMAGE-2 team tried to set up a truly independent validation exercise by starting the model in 1900 and simulating the twentieth century. The first step of this validation exercise was to develop a historic database of all relevant drivers. The resulting HYDE database (documented in (Goldewijk 2001)) would then be used to initialize the model, after which trends and results would be compared with known trends and outcomes. The match was perfect, which created suspicion. A major problem of this validation exercise was the actual coverage of the data. Before the Second World War much of the agricultural sector was already covered in global summary statistical databases but much of forestry and energy data were still part of an informal economy and only little data with adequate coverage was available. In HYDE gaps were filed with backward extrapolation of recent trends, model-based reconstructions based on models similar to those used in IMAGE-2, etc. Other available long-term global historic databases involve similar problems. The validation exercise was thus not independent at all and had little scientific significance.

IFs: Barry Hughes developed the International Futures simulator (IFs) inspired by the following world models: the Mesarovic-Pestel or World Integrated Model (Mesarovic and Pestel 1974, Hughes 1980), the Leontief World Model (Leontief 1977), the Bariloche Foundation's world model (Herrera et al. 1976), and the Systems Analysis Research Unit Model (SARU (Systems Analysis Research Unit) 1978). IFs are global modeling system based on a data base derived for 182 countries since 1960. Components of the model include a population module, an economic module, an agricultural module, an energy module, a social and international policy module, an environmental module, and a technical module. The population module follows 22 age-sex cohorts to old age with cohort-specific fertility and mortality rates of households in response to income and income distribution to simulate average life expectancy at birth, literacy rate, and overall measures of human development (HDI) and physical quality of life. The population model represents migration among the countries and shows the effects of HIV/AIDS. A recent development includes a submodel of formal education.

The economic module is a general equilibrium-seeking algorithm based on a Cobb-Douglas production function that represents the economy in six sectors: agriculture, materials, energy, industry, services, and technology. It computes and uses input-output matrices that change dynamically with development level.

The agricultural model is a partial equilibrium model that represents production, consumption and trade of crops and meat, ocean fish catch and aquaculture. This model maintains land use in crop, grazing, forest, urban, and "other" categories dependent on the demand for food, livestock feed, and industrial use of agricultural products. The energy module is a partial equilibrium module to consider known reserves, consumption and trade of oil, gas, coal, nuclear, hydroelectric, and other renewable energy forms. It portrays changing capital costs of each energy type with technological change as well as with draw-downs of resources.

The political module includes national and international politics. The national politics module computes fiscal policy, 6 categories of government spending: military, health, education, R&D, foreign aid, and a residual, and computes changes in social conditions, attitudes and the social organization. The national politics modules allows for the evolution of democracy and prospects for state failures. The international political module traces changes in power balances across states and region.

The environmental module tracks the remaining resources of fossil fuels, area of forested land, of water usage, and atmospheric carbon dioxide emissions.

Technology solutions are distributed throughout the model and represent the assumptions about rates of technological advance in agriculture, energy, and the broader economy. Technological advances are tied to the extent of electronic networking of individuals in societies and are dependent on the governmental spending model with respect to research and development.

The International Futures model has the most sophisticated and user-friendly GUI of all the models explored. It has recently been launched on the World Wide Web so that users can run scenarios over the Internet and instantly generate output graphs and comparisons between scenarios either globally or for selected countries. IFs represent the most highly articulated socioeconomic model in our collection of IGMs, but its natural systems components are rather bare bones. It treats nature as resource sources and sinks, but with no articulation of the internal dynamics of the natural system.

Originally developed for educational purposes, more recently IFs' main function has been that of a policy tool. The International Futures model is used by the National Intelligence Council Project 2020, which aims to provide U.S. policymakers with future world developments that should inform policy decisions. It is also being employed in developing and analyzing scenarios for the UNEP GEO-4 report (in conjunction with IMAGE-2 and several other thematic models) and has been used to assess explicitly the attainment of the Millennium Development Goals (MDGs) outlined by the UNDP in 2004.

The model simulates onward starting at the initial year 2000 (Hughes 1996, Hughes 2004). The model focuses on capturing trends in the next 10–20 years, although projections out to 2300 are produced for some audiences. The simulations account for changing consumption patterns and international trade. The model uses a social accounting matrix envelope to tie economic production and consumption to financial flows.

The IFs model has undergone some historic calibration; however, the results are not easily available. Because the relationships driving the model are derived from historic data, the developers of IFs have instead focused on comparative analyses with multiple other model forecasts (Hughes 2004) in each of the issue areas captured by the model. Validation of the model proved difficult in the late 1980s (Liverman 1987). Since then, model assumptions, structure, and resolution have been improved. A similar validation exercise would be useful in demonstrating the suitability of the IFs model for global simulation.

DICE: The Dynamic Integrated Climate and the Economy (DICE) model (Nordhaus 1994) was developed in the early 1990s to investigate the economics of climate change. DICE is the simplest of the models evaluated in this review. The only biophysical process incorporated in the model is a very simple treatment of climate change. The optimization approach in this model is distinctly different from the systems approach taken in most of the other models considered in this review.
As mentioned above, the Ramsey model of optimal economic growth used as the basis for DICE *assumes* that economic growth is not limited by natural resources or environmental changes. Economic output in DICE is estimated using a production function which includes only reproducible capital, labor, and technology in its arguments. Population growth and technological change are exogenous and natural capital is completely missing. These are rather strong assumptions, given that one of the purposes of the DICE model is to integrate economic models with the rest of the natural world. In DICE, the economy goes on its merry way with no real *feedback* from the natural world. There is only the one-way flow of impacts on climate, and only through that on agriculture and ecosystems. Other work on an economic growth model with natural resources in the production function and endogenous population growth shows some very different results (Brown and Roughgarden 1995), so we can assume that adopting something other than the standard neoclassical growth model would make a big difference to the conclusions.

In addition, both the spatial and temporal resolution of the DICE model are very low, given the problem at hand. DICE is globally averaged and uses a time step of 10 years. Finally, DICE assumes that consumption equals welfare: "We assume that the purpose of our policies is to improve the living standards or consumption of humans now and in the future." (pp. 10). This is one purpose, but consumption is not always correlated with overall human well-being or welfare, more broadly defined (e.g., (Easterlin 1974, Daly and Cobb 1989, Ekins and Max-Neef 2006)). The problem is that material growth in the economy can become "anti-economic" if the many uncounted costs of additional growth begin to outweigh the counted benefits (Daly and Cobb 1989). The DICE model, through its simple damage function, includes only a very crude estimate of some of these costs, but it has no way of picking up any non-consumption welfare effects or feedback effects from the environment to the economy. What DICE actually models is (at best) the marketed, and some small piece of the non-marketed, consumption effects, and these may in fact be opposite to the true welfare effects as the planet's natural capital base continues to erode. Quoting from Nordhaus (1994): "The basic approach of the DICE model is to use a Ramsey model of optimal economic growth with certain adjustments and to calculate the optimal path for both capital accumulation and GHG-emissions reductions" (p. 5). This was done by incorporating a greatly simplified depiction of the global atmosphere to form a set of climate-emissions-damage equations. While the simplified climate equations might pick up the major features of the emissions-climate link, the link in the model between climate change and economic impact on human and natural systems is by far the weakest one. To pick this up, the DICE model assumes a very simple relationship between global mean temperature (as a proxy for climate change) and damage: D(t)/Q(t) = .00144 T(t)2, where D is the loss of global output, Q is global output, and T is global mean temperature, all at time t ((Nordhaus 1994), eq. 2.11, p. 18). The missing links are the actual feedbacks between climate change (including the more important features of precipitation change and especially the geographic distribution of changes) and ecosystem changes, and between ecosystem changes and economic performance. These links are complex, yet they are the essence of the problem being addressed. While integrated climate–economy–ecosystem models are still relatively rare (Parson and Fisher-Vanden 1994), there are several others (see above and below) which do a fairly elaborate, spatially explicit, job of estimating the climate–ecosystem linkages, and the results are anything but simple.

As Nordhaus (1973) has himself pointed out, any model is only as good as the assumptions that go into it. In the case of the DICE model, a thorough job has been done in analyzing the model's sensitivity to uncertainty about the parameters, but no effort went into analyzing sensitivity to some of the more basic, and more important, assumptions.

Given that most of the underlying relationships are probably highly nonlinear and spatially discontinuous, this level of aggregation has got to cause some serious problems. As Nordhaus has himself pointed out elsewhere: "The main result of aggregation theory is that aggregation is generally possible only when the underlying micro relations are linear" ((1973), p. 1160). This, combined with the simple basic structure of DICE, means that there are no real possibilities for "surprises" in DICE like the kind we have come to expect in the real world, and that can emerge from some of the other models reviewed here. Yet, there is no discussion of the possibly huge impacts of aggregation error other than Nordhaus's contention that the level of aggregation used was necessary in order that "the theoretical model is transparent and the optimization model is empirically tractable." Good goals, but hardly justification for a model intended to be used to set realistic global policies on greenhouse warming. Some of these critiques have been addressed in RICE, a recent extension of the DICE model. RICE improves spatial resolution by modeling 6–10 regions separately (Nordhaus 1973, Nordhaus and Yang 1996). Further improvements on the model, including an assessment of uncertainty, are currently under development in another version called PRICE.

There is some attempt to broaden the concept of consumption beyond conventional GNP by stating that consumption "includes not only traditional market purchases of goods and services like food and shelter but also nonmarket items such as leisure, cultural amenities, and enjoyment of the environment" (Nordhaus 1994, p. 10). After saying this, these nontraditional components are quickly forgotten, and the productive values of natural capital (which are probably more important) are never even considered.

TARGETS: Targets (Tool to Assess Regional and Global Environmental and health Targets for Sustainability;(Rotmans and De Vries 1997)) is also a direct descendent of IMAGE. It aimed to redirect and accelerate the discussions from climate change towards global change. Its main innovation was that the model assumed that changes in drivers were a direct function of different perspectives on how the world system functions and is managed. The drivers thus do not define boundary conditions but are an integral part of the model itself. A future, as defined by TARGETS, provides the different implications of such a perspective in terms of population and health, energy, use of land and water, and biogeochemical cycles. Another new aspect is not to list the absolute impacts but indicate them in terms of risks for unsustainable developments.
TARGETS consists of five submodels: population and health, energy, land and food, and water. Each of those submodels is a DPSIR model but they are linked through a socioeconomic scenario generator, in which policy responses are explicitly incorporated. All submodels can be used in a stand-alone mode as well, in order to allow model and data comparisons, comparisons with other models, and targeted validation and sensitivity analysis. The TARGETS approach does not provide simple answers and again stresses that the future

is highly uncertain. It generates insights in the accelerating influence of the human race and as such strongly supports the notion of the Anthropocene (Crutzen and Steffen 2003). It also provides a new insight (not appreciated by many modelers) that individual people perceive changes in their environment differently, which influences the rationale for selecting appropriate responses. TARGETS is not used to develop scenarios, but utopias: Worlds dominated by a particular world view or perspective. TARGETS was quite influential in setting the stage for the acceptance of the narrative scenarios approach, later also adopted by the IPCC SRES scenarios (Nakicenovic et al. 2000) and by the MEA (2005).

The model is thus strongly based on the concept of cultural perspectives to deal with the apparent uncertainty in the interactions between humans and their natural environment (van Asselt and Rotmans 2002). The natural and socioeconomic dimensions are highly integrated in TARGETS. As such it has departed from the simpler causal chain or DPSIR (Driver-Pressure-State Change-Impact-Response) models as used earlier. TARGETS is based on the basic notion that in the absence of complete knowledge and in order to guide choices and actions, people use stylized and simplified images of the world around them. These images are based on experiential trends interpreted by implicit rules. This complex represents human values and beliefs. These images further form the bases of different world views and also determine the behavior of people and thus their interactions in the Earth system.

Although innovative and challenging, the stakeholders evaluating the model results had large difficulties in understanding the role of all these perspectives (see, e.g., the Ulysses project: http://zit1.zit.tu-darmstadt.de/ulysses). Additionally, the lack of spatial detail for the land, water, and biogeochemical simulations was also seen as a major drawback.

GUMBO: The Global Unified Metamodel of the BiOsphere (GUMBO; (Boumans et al. 2002)) was developed as part of a working group at the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, CA. Its goal was to simulate the integrated earth system and assess the dynamics and values of ecosystem services. It is a “metamodel” in that it represents a synthesis and a simplification of several existing dynamic global models in both the natural and social sciences at an intermediate level of complexity. The current version of the model contains 234 state variables, 930 variables total, and 1715 parameters. GUMBO is the first global model to include the dynamic feedbacks among human technology, economic production and welfare, and ecosystem goods and services within the dynamic earth system. GUMBO includes five distinct modules or “spheres”: the Atmosphere, Lithosphere, Hydrosphere, Biosphere, and Anthroposphere. The Earth’s surface is further divided into eleven biomes or ecosystem types, which encompass the entire surface area of the planet: *Open Ocean*, *Coastal Ocean*, *Forests*, *Grasslands*, *Wetlands*, *Lakes/Rivers*, *Deserts*, *Tundra*, *Ice/rock*, *Croplands*, and *Urban*. The relative areas of each biome change in response to urban and rural population growth, Gross World Product (GWP), and changes in global temperature. Among the spheres and biomes, there are exchanges of energy, carbon, nutrients, water and mineral matter. In GUMBO, ecosystem services are aggregated to 7 major types, while ecosystem goods are aggregated into 4 major types. Ecosystem services, in contrast to ecosystem goods, cannot accumulate or be used at a specified rate of depletion. Ecosystem services include: soil formation, gas regulation, climate regulation, nutrient cycling, disturbance regulation, recreation and culture, and waste assimilation. Ecosystem goods include: water, harvested organic matter, mined ores, and extracted fossil fuel. These 11 goods and services represent the output from natural capital, which combines with built capital, human capital, and social capital to produce economic goods and services and social welfare. The model calculates the marginal product of ecosystem services in both the production and welfare functions as estimates of the shadow prices of each service. Historical calibrations from 1900 to 2000 for 14 key variables for which quantitative time series data was available produced an average R^2 of 0.922. A range of future scenarios to the year 2100 representing different assumptions about future technological change, investment strategies and other factors have been simulated. The scenarios include a base case (using the "best fit" values of the model parameters over the historical period) and four initial alternative scenarios. These four alternatives are the result of two variations (a technologically optimistic and skeptical set) concerning assumptions about key parameters in the model, arrayed against two variations (a technologically optimistic and skeptical set) of policy settings concerning the rates of investment in the four types of capital (natural, social, human, and built). They correspond to the four scenarios laid out in Costanza (2000), and are very similar to the four scenarios used in the Millennium Ecosystem Assessment. The outputs of the GUMBO model includes the following

A high level of dynamic integration between the biophysical earth system and the human socioeconomic system is important if we are to further develop integrated models with predictive capabilities. Preliminary calibration results across a broad range of variables show very good agreement with historical data. This builds confidence in the GUMBO model and also constrains future scenarios. The model produced a range of scenarios that represent reasonable rates of change of key parameters and investment policies, and these bracketed a range of future possibilities that can serve as a basis for further discussions, assessments, and improvements. Any user can change these parameters further and observe the results.

Assessing global sustainability can only be done using a dynamic integrated model. However, one is still left with decisions about *what* to sustain (i.e., GWP, welfare, welfare per capita, etc.). GUMBO allows these decisions to be made explicitly and in the context of the complex world system. It allows both desirable and sustainable futures to be examined.

Ecosystem services are an important link between the biophysical functioning of the earth system and the provision of sustainable human welfare. The physical and value dynamics are quite complex. The overall value of ecosystem services, in terms of their relative contribution to both the production and welfare functions, is shown to be significantly higher than GWP (4.5 times in this version of the model).

"Technologically skeptical" investment policies are shown to have the best chance (given uncertainty about key parameters) of achieving high and sustainable welfare per capita. This means increased relative rates of investment in knowledge, social capital, and natural capital, and reduced relative rates of consumption and investment in built capital. The GUMBO model is available over the internet but requires the STELLA software for the user to run. The GUI developed for GUMBO is built into the STELLA software, but does not come with instructions or guidance.

Other models and frameworks

Climate Change Models: In order to reduce the risks and uncertainties associated with future climate change, such as for instance disequilibrium dynamics in vegetation distribution (Svenning and Sandel 2013), will also be necessary to generate sustainable landscape management. Future climate projections can be factored in to understand ecological responses to climate, thus the impact of climate change on the future provision of ecosystem services at the global scale. The outputs of Global Circulation Models (GCMs) are coarse (at ~ 50km pixel) but they can be downscaled using three different techniques, so to gain pixel resolution for regional applications. The techniques used to gain pixels resolution are: statistic or dynamic downscaling, and simple scaling. The advantages and disadvantages of each of these techniques are discussed in detail by (Harris et al. 2014b). The main message is

that the degree of uncertainty is lower in dynamically downscaled maps than in statistically downscaled maps, which on the other hand uses less computational effort. However, before choosing a particular GMS as an input variable, it is important to have a good understanding of the strengths and weaknesses of the future climate projections because the choice of GCMs will make a strong impact on the results. For example, an ecology study that accounted for the most important sources of uncertainty in species distribution models (Diniz-Filho et al. 2009) found that ~60% of the uncertainty could be attributable to the different statistical techniques employed to map the species distribution, whereas the rest of the uncertainty could be attributed to the GCMs.
The Intergovernmental Panel on Climate Change (IPCC) released the Fifth report in 2013, which includes more than 50 GCMs. These models are not ranked by the IPCC, so is not possible to select the '*best*' or '*worst*' model. In the practice, including more than 50 GCMs plus the corresponding emission scenarios into the analysis is unrealistic, so the question is how to determine which ones are to be used. The recommendation made by the experts is to select a range of GCMs that depict all possible variability of these plausible future projections (Harris et al. 2014a). A common approach to deal with the uncertainty and variability of the GCMs is to use a multi-model ensemble (Araújo and New 2007, Diniz-Filho et al. 2009, Grenouillet et al. 2011). The multi-model ensemble is, to date, the most accepted approach that accounts for the variance and uncertainty of future climate projection.

Models Specifically Aimed at Ecosystem Services: In addition to GUMBO described above, several other models and analytical tools have been developed that are specifically aimed at assessing ecosystem services. These models, or an adaptation, can address knowledge gaps such as lack of mapping and specific types of non-marked values of ecosystem services and offer a robust low cost method of quantifying ecosystem services(ELD-Initiative 2013). Most of the models are spatially explicit, some are dynamic. The best summary of these approaches is in (Bagstad et al. 2013). Table 4 is an extract from that paper that lists these models and tools along with brief descriptions.

Table 4. A survey of ecosystem services tools *(adapted from(Bagstad et al. 2013))*

Name	Tool, URL, and references	Brief description
Ecosystem Services Review (ESR)	http://www.wri.org/, (World Resources Institute (WRI), 2012)	Publicly available, spreadsheet-based process to qualitatively assess ecosystem services impacts.
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	http://www.naturalcapitalproject.org, (Kareiva et al., 2011 and Tallis et al., 2013)	Open source ecosystem service mapping and valuation models accessed through ArcGIS.
Artificial Intelligence for Ecosystem Services (ARIES)	http://www.ariesonline.org (Bagstad et al., 2011 and Villa et al., 2011)	Open source modeling framework to map ecosystem service flows; online interface and stand-alone web tools under development.
LUCI (formerly Polyscape)	http://www.polyscape.org (Jackson et al., 2013)	Open source GIS toolbox to map areas providing services and potential gain or loss of services under management scenarios.
Multiscale Integrated Models of Ecosystem Services (MIMES)	http://www.afordablefutures.org	Open source dynamic modeling system for mapping and valuing ecosystem services.
EcoServ	(Feng et al., 2011)	Web-accessible tool to model

		ecosystem services.
Co$ting Nature	http://www1.policysupport.org/cgi-bin/ecoengine/start.cgi?project=costingnature	Web-accessible tool to map ecosystem services and conservation priority areas.
Social Values for Ecosystem Services (SolVES)	http://solves.cr.usgs.gov (Sherrouse et al., 2011)	ArcGIS toolbar for mapping social values for ecosystem services based on survey data or value transfer.
Envision	http://envision.bioe.orst.edu, (Guzy et al., 2008)	Integrated urban growth-ecosystem services modeling system; has used external models, including InVEST, or created new ecosystem service models as appropriate.
Ecosystem Portfolio Model (EPM),	http://geography.wr.usgs.gov, (Labiosa et al., 2013)	Web-accessible tool to model economic, environmental, and quality of life impacts of alternative land-use choices.
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EcoMetrix	http://www.parametrix.com (Parametrix, 2010)	Proprietary tool for measuring ecosystem services at site scales using field surveys.
Natural Assets Information System (NAIS)	http://www.sig-gis.com, (Troy and Wilson, 2006)	Proprietary valuation database paired with GIS mapping of land-cover types for point transfer.
Ecosystem Valuation Toolkit	http://www.esvaluation.org (Ecosystem Valuation Toolkit, 2012)	Subscription-based valuation database paired with GIS mapping of land-cover types for point transfer.
Benefit Transfer and Use Estimating Model Toolkit	http://www.defenders.org (Loomis et al., 2008)	Publicly available spreadsheets, use function transfer to value changes in ecosystem services in the U.S.

One of these tools is the Multiscale Integrated Models of Ecosystem Services (MIMES) framework. MIMES aims to address the magnitude, dynamics, and spatial patterns of ecosystem services at multiple scales. The MIMES framework builds on the GUMBO model described above, but is spatially explicit and scalable. It explicitly addresses the linked dynamics of natural, human, built and social capital, and allows one to integrate site-specific information with regional and global surveys, GIS, and remote sensing data. MIMES is process-based, spatially explicit, dynamic, non-linear simulation model (including carbon, water, nitrogen, phosphorous, plants, consumers (including humans) and a range of ecosystem services) under various climate, economic, and policy scenarios. MIMES is

spatially scalable in that it can be applied at multiple spatial and temporal scales from farms to watersheds to countries to globally.
Each “location” in MIMES includes the percent of the land surface in eleven biomes or ecosystem types: *Open Ocean*, *Coastal Ocean*, *Forests*, *Grasslands*, *Wetlands*, *Lakes/Rivers*, *Deserts*, *Tundra*, *Ice/rock*, *Croplands*, and *Urban.* The relative areas of each biome at each location change in response to urban and rural population growth, economic production, changes in temperature and precipitation and other variables. Among the biomes, there are exchanges of energy, carbon, nutrients, water and mineral matter. The model calculates the marginal product of ecosystem services in both an economic production and welfare function as estimates of the shadow prices of each service. The number of “locations” or cells in MIMES is variable and can include either grid or polygon representations of multiple locations. For each of these applications, the basic MIMES structure remains the same but the parameters must be recalibrated.

Conventional economic valuation presumes that people have well-formed preferences and enough information about trade-offs that they can adequately judge their “willingness-to-pay.” These assumptions do not hold for many ecosystem services. Therefore, we must: (1) inform people’s preferences (for example by showing them the underlying dynamics of the ecosystems in question using models like MIMES; (2) allow groups to discuss the issues and “construct” their preferences (again using the MIMES framework to inform the discussions); or (3) use other techniques that do not rely on preferences to estimate the contribution to human welfare of ecosystem services (i.e. using MIMES to directly infer marginal contributions to welfare). These three methods can be combined to develop new and more integrated methods to value ecosystem services.

Other models and frameworks

Climate Change Models

To reduce the risks and uncertainties associated with future climate change, it will also be necessary to generate sustainable landscape management. Future climate projections can be factored in to understand ecological responses to climate, thus the impact of climate change on the future provision of ecosystem services at the global scale. The outputs of Global Circulation Models (GCMs) are coarse (~50km pixel), but can be downscaled using three different techniques, so as to gain appropriate pixel resolution for regional applications. The techniques used to gain pixels resolution are: statistic or dynamic downscaling, and simple scaling. The advantages and disadvantages of each of these techniques are discussed in detail by (Harris et al. 2014b). The main message is that the degree of uncertainty is lower in dynamically downscaled maps than in statistically downscaled maps, which, on the other hand, uses less computational effort. However, before choosing a particular GCM as an input variable, it is important to have a good understanding of the strengths and weaknesses of the future climate projections, because the choice of GCMs will make a strong impact on the results. For example, an ecology study that accounted for the most important sources of uncertainty in species distribution models (Diniz-Filho et al. 2009) found that ~60 per cent of the uncertainty could be attributed to different statistical techniques employed to map the species distribution, whereas the rest of the uncertainty could be attributed to the GCMs.

The IPCC released their fifth report in 2013, which included more than 50 GCMs. These models are not ranked by the IPCC, so is not possible to select the ‘best’ or ‘worst’ model. Including more than 50 GCMs plus the corresponding emission scenarios into an analysis is unrealistic, so the question is how to determine which ones are to be used. The recommendation made by the experts is to select a range of GCMs that depict all possible variability of these plausible future projections (Harris et al. 2014a). A common approach to deal with the uncertainty and variability of the GCMs is to use a multi-model ensemble (Araújo and New 2007, Diniz-Filho et al. 2009, Grenouillet et al. 2011). The multi-model ensemble is, to date, the most accepted approach that accounts for the variance and uncertainty of future climate projection.

The **PRECIS** model is a dynamical downscaling, Regional Climate Model (RCM). It is a downloadable model (http://metoffice.gov.uk/precis) that covers the globe at a regional level ~50km. Simple Scaling is available as a module of the WorldClim (the Delta Module) (http://worldclim.org), which is available on a 1km scale.

Statistical downscaling models include **CLIMGEN** (Mitchell et al. 2004), another module of WorldClim (Hijmans et al. 2011) also scaled down to cover ~1km (http://worldclim.org). CliMond (Kriticos et al. 2012) is also a statistical downscaling at ~20km resolution (https://climond.org). Other models cover single sites such as the Statistical Downscaling Model (SDSM) (Wilby et al. 2002) (http://sdsm.org.uk) or Automatic Statistical Downscaling (ASD) (Hessami et al. 2008) (http://cccsn.ec.gc.ca).

GIAM (Global Integrated Assessment Model) is an assessment model developed by Department of Environment and CSIRO (Australia) and allows feedbacks and interactions between climate and economic systems. This gives the model capacity to provide comprehensive information on physical and economic impacts of the changing climate.

INFFER

The Investment Framework For Environmental Resources (http://inffer.com.au) is a not a climate model, but a framework for assessing and developing environmental restoration projects (Pannell et al. 2012). This framework could be helpful to address the overall costs/benefits of different land management interventions, as mentioned in the ELD Initiative (p61, box 9, no. 1). It is originally based on the Salinity Investment Framework III, but evolved into INFFER, to be able to handle a broad suite of environmental problems and restoration efforts. INFFER is implemented in Australia, China, Europe, and North America, and is a framework tool to help develop projects and identify either which projects are feasible, or what the highest priorities of the different projects should be. The interesting part of the INFFER framework is that it is developed to specify the cost-effectiveness of the project and thus take the economic perspective and project financing into account, which is similar to the goals of the ELD Initiative. The framework consists of 7 steps and each goal of the project must be SMART – specific, measurable, achievable, relevant, and time-bound.

Information on project goals, strengths and weaknesses, time lags and effectiveness, adoption of actions by the public, delivery mechanisms and costs, are used to address and assess public and private benefits for the stakeholders. All this information is used to calculate a cost-benefit index (or ratio depending on whether a valuation study is performed), risk factors (e.g., technical feasibility, funding constraints, social or political issues), externality, quality of project, and lastly, identify key knowledge gaps. The Public: Private Benefits Framework used in INFFER is intended to determine the proper policy mechanisms for inducing wanted changes in stakeholder behavior in a project, which also need to be determined (Pannell et al. 2012, ELD-Initiative 2013).

CLUE

Another interesting tool to determine relevant scenarios is to model the effects of land use change, using the Conversion of Land Use and its Effects modelling framework (CLUE). It was developed to mimic land use change, and was based on predetermined relationships between land use maps and driving forces in conjunction with dynamic modelling of competitive or opposing demands for land uses. Even though this model is integrative and has applications for many different countries, the model holds only one value per pixel. To also be able to analyze regional scale landscapes, the CLUE-S was developed, as the original CLUE only operates on national or continental scale with a coarse spatial resolution (Verburg et al. 2002). The above-mentioned examples are based on remotely sensed data and land cover. Noting that land cover and land use are different and yet intertwined is part of the difficulty in selecting and developing a classification scheme.

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Models Specifically Aimed at Ecosystem Services

In addition to GUMBO, several other models and analytical tools have been developed that are specifically aimed at assessing ecosystem services. These models, or adaptations of them, can address knowledge gaps such as lack of mapping and specific types of non-marked values of ecosystem services and offer a robust low cost method of quantifying ecosystem services (ELD Initiative 2013, p61, box 9, no. 7-9). Most of the models are spatially explicit and some are dynamic. The best summary of these approaches is found in Bagstad et al. (2013). Table 4 in this report is an extract from that paper and lists these models and tools along with brief descriptions.

One of these tools that that the authors feel particularly captures the needs of the ELD Initiative going forward is the Multiscale Integrated Models of Ecosystem Services (MIMES) framework. MIMES aims to address the magnitude, dynamics, and spatial patterns of ecosystem services at multiple scales. The MIMES framework builds on the GUMBO model described above, but is spatially explicit and scalable. It addresses the linked dynamics of natural, human, built, and social capital, and allows one to integrate site-specific information with regional and global surveys, GIS, and remote sensing data. MIMES is process-based, spatially explicit, dynamic, non-linear simulation model (including carbon, water, nitrogen, phosphorous, plants, consumers (including humans) and a range of ecosystem services) under various climate, economic, and policy scenarios. MIMES is spatially scalable in that it can be applied at multiple spatial and temporal scales from farms to watersheds, countries, and globally.

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and Tradeoffs (InVEST)	2011 and Tallis et al., 2013)	accessed through ArcGIS.
Artificial Intelligence for Ecosystem Services (ARIES)	http://www.ariesonline.org (Bagstad et al., 2011 and Villa et al., 2011)	Open source modeling framework to map ecosystem service flows; online interface and stand-alone web tools under development.
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Each 'location' in MIMES includes the percent of the land surface in eleven biomes or ecosystem types (same as GUMBO): *open ocean*, *coastal ocean*, *forests*, *grasslands*, *wetlands*, *lakes/rivers*, *deserts*, *tundra*, *ice/rock*, *croplands*, and *urban.* The relative areas of each biome at each location change in response to urban and rural population growth, economic production, changes in temperature and precipitation, and other variables. Among the biomes, there are exchanges of energy, carbon, nutrients, water, and mineral matter. The model calculates the marginal product of ecosystem services in both an economic production and welfare function as estimates of the shadow prices of each service. The number of 'locations"' or cells in MIMES is variable and can include either grid or polygon representations of multiple locations. For each of these applications, the basic MIMES structure remains the same but the parameters must be recalibrated.

Conventional economic valuation presumes that people have well-formed preferences and enough information about trade-offs that they can adequately judge their 'willingness-to-pay. These assumptions do not hold for many ecosystem services. Therefore, analyses must be tailored to: (1) inform people's preferences (for example by showing them the underlying dynamics of the ecosystems in question using models like MIMES), (2) allow groups to discuss the issues and 'construct' their preferences (again using the MIMES framework to inform the discussions), and (3) use other techniques that do not rely on preferences to estimate the contribution to human welfare of ecosystem services (i.e., using MIMES to directly infer marginal contributions to welfare). These three methods can be combined to develop new and more integrated methods to value ecosystem services.

MIMES is still under development, but the ELD Initiative could be a venue to further develop and apply this framework in a participatory way and perhaps with advanced gaming interfaces (see below).

In summary, the above mentioned types of integrated spatially explicit models are key to describe complex human-nature coupled systems, because of the strong geographical component as well as their utility for a dissemination and communication (Sui and Goodchild 2001). Depending on the context of the chosen site and the integral part it plays in the overall biosphere (Foley et al. 2011), the choice of model or component will vary. Causal relationships between system variables are not simple and are affected by context, exogenous factors, and the presence or absence of positive and negative feedback loops (Sterman 2000). This implies that adequately modelling land degradation and restoration require an approach capable of handling these features, such as systems dynamics modelling integrated with agent-based modelling.

Participatory Model Development:

Although there is an impressive suite of models and frameworks to date that can help represent and analyze the context of land degradation, more information is needed to improve on the mentioned limitations. One suggestion is to increase the participatory stakeholder involvement methods, which seeks to assess benefits to individuals (including ones that are not so well perceived), whole communities, and sustainability (Costanza 2000).

By working together with multiple stakeholders in open dialogue (e.g., at workshops), knowledge of a complex system can be increased significantly (Kenter et al. 2011). Stakeholders can inform participants on the bigger picture, and individuals' incorrect knowledge can be corrected in dialogue and training sessions. Through participatory mapping and valuation exercises, it is possible to engage groups of stakeholders in generating a better picture that takes all the components of these systems into account {Walker, 2002 #17;Mendoza, 2005 #18;Costanza, 1998 #23}. The knowledge of land managers is a valuable asset in this approach (Pretty 2008). Furthermore, stakeholders are critical in developing and testing the scenarios for exploring the future of SLM and finding viable solutions to the problems. This method enables all parties to participate in understanding and valuing the landscape in a holistic approach to land management, from decision-makers, academics, and farmers, to business leaders and recreationalists. Through these participatory engagements, it is possible to explore the design for ecosystem services to be integrated with the production of conventional commodities, and thus solving issues of ecological degradation. Training local researchers and business personnel to use systems dynamics modelling for ecological assets is expected to accelerate solution adoption and improve innovation and collaboration capacity

Advanced, multi-scale user interfaces and games

Using a computer-based system allows participants to make decisions based on information provided by a user interface, and allows for information and resulting behaviors to be presented rapidly. Thus further allows for more information provision, decision-making points, and a greater number of repeated trials. Behind the user interface there is an underlying dynamic simulation model that updates the games database as decisions are made. Janssen et al. (2010) conducted a series of computer-based experiments to test the impact of communication and punishment in common-pool resource management. They found that respondents are willing to engage in punishing defectors even at personal cost, however, punishment without communication does not increase overall payoffs.

Heckbert et al. (2011) present an integrated GIS- and agent-based model with an experimental economics platform where participants take on the role as an agent, or avatar, in a dynamic simulation model of agricultural land management. This example shows the progression of experiments towards multi-player gaming, however, experimental economics usually recommends omitting context and complexity from the decision-making situation in

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order to isolate the influence of a given tradeoff decision. For example, in the (Heckbert et al. 2011) application, experiment participants applied ‘inputs’ to ‘production’ rather than ‘fertilizer’ to ‘agriculture’, to avoid social biases regarding the system they were managing. In the Janssen et al. (2010) example, participants use an abstract gridded board with tokens to represent a common-pool resource – not unlike common board games (e.g., backgammon, checkers).

Dynamic modelling’s strength is simulating links between human decisions and ecosystem functioning, but used alone, it still lacks a human component. Thus, for research purposes, the authors of this report would like to have an interactive gaming platform on top of an ecosystem simulation model that would allow individuals to ‘play’ the system to create their version of the ‘best’, highest quality of life, world. Since the model can embed the trade-offs between, for example, a better environment and food production, the choices players make during the game will reflect how they value tradeoffs like these. Information that reveals the nature of interactions among players may also prove useful. This is somewhat like a conventional choice experiment (Wilson and Carpenter 1999, Colombo et al. 2011) except that players are able to create their own scenarios rather than the researcher presenting them with a fixed set. Preferences can also emerge as a result of learning about the system or from group interactions. The advantages of using a computer game to capture data about preferences include:

- The ability to quickly replicate experiments;
- A large potential data pool, with potential sample sizes in the thousands;
- The ability to track and record player decisions through in-built survey mechanisms;
- Removing a degree of interviewer bias by enabling users to interact directly with an experiment rather than via an interviewer (albeit, the experiment is one step removed from the game developers or surrogate interviewers);
- The ability to place people's choices within contexts that are (potentially) more realistic than the typical context-neutral experimental form, and;
- Assessing whether increasing degrees of game 'realism' (complexity), or introducing different elements within a game, affects people’s valuations and preferences.

There is, of course, the unresolved question of whether players will value things in the game context the same way they do in real life, but this problem is also applicable to experimental economics studies, and is not unique to this type of valuation technique.

Substantial literature on simulation modelling for ecosystem services is available at scales that can form the basis for these games (Boumans et al. 2002, Costanza and Voinov 2003, Craft et al. 2008, Arkema and Samhouri 2009, Nelson et al. 2009) including the MIMES framework mentioned above. However, these models have yet to be used for integrating gaming. By combining scientific understanding of how ecosystems function (embedded in dynamic landscape models) with the ability to quickly and cheaply solicit input from a broad range of participants, this approach could have a huge impact on how ecosystem service valuation and management is done. This would dramatically improve the ability to understand and manage ecosystems and benefit society at large.

Alternative Futures

One way to use the models and data described above is to generate and evaluate scenarios that embody different possibilities. Bateman et al. (2013) is a good example of this approach. They evaluated six scenarios for UK agriculture and ecosystem services using a range of models. Results showed that scenarios (and their underlying policies) that included the value of ecosystem services were an order of magnitude more valuable than those that focused only on conventional marketed agricultural products.

The goal of the ELD Initiative is ultimately to do something similar for other regions, countries, and globally. To do this, the authors suggest scenarios be developed that cover, at minimum, the following four possible futures:

1. Focus on GDP growth with continued land degradation;
2. Maintain current practices in an energy-constrained world;
3. Repair the damage, and;
4. Geographically appropriate, integrated and sustainable land use and management that adequately accounts for the value of ecosystem services.

These scenarios will be developed and evaluated as the Initiative moves forward.

The Way Forward

Sustainable land management can reverse the land degradation trends the world is seeing. An example from arid rural Australia is that an increase in the proportion of perennial plants, in particular grasses, can cause soil regeneration and increased biodiversity, which enhances the ecosystem services (Culman et al. 2010, Glover 2010, Ampt and Doornbos 2011, Teague et al. 2011, Weber and Gokhale 2011, Kremen and Miles 2012, Bommarco et al. 2013, Coonan 2013).

The ELD Initiative is similar to the Bateman et al. (2013) UK-NEA. It is based on evaluating land use and management scenarios based on an inclusive assessment of the total value of the land and the methodology addresses solutions to many of the knowledge deficits raised by the ELD Initiative (2013). However, new questions are raised and the following challenges for this type of assessment must be considered:

(i) total economic valuation is currently perceived as too complicated, too costly to estimate, and/or its results are not considered appropriately in the decision;
(ii) there is no unique method to measure total economic values;
(iii) there is not yet a complete set of methods that are simple to implement and lead to robust estimates of the total economic value of land, and;
(iv) there are no studies to date that estimate the full economic value of a piece of land based on the range of provided services. Valuations have thus always been only partially complete, making comparisons between sites difficult, if not impossible, as different aspects of land and ecosystem services can be measured in very different ways.

The challenge for the ELD Initiative is to overcome these problems and produce a set of tools and techniques that can better assess the true value of land in a consistent, credible, and relatively inexpensive way.

Based on this review of methods, data, and models, the authors can offer the following vision for what a system that meets these needs could look like. The system would be based on an integrated, dynamic, spatially explicit, scalable computer simulation model (something like MIMES) that has been developed in a participatory way and calibrated at a number of sites around the world. This general model could be parameterized with global GIS data sets over the internet. The user interface would allow individual users to specify any area of the earth and be able to run a version of the model that would provide dynamics and values of natural capital and ecosystem services along with built, human, and social capital. It would also allow land use policy scenarios to be quickly run and compared. An advanced gaming interface would allow the model to be 'played' by a large number of people and their trade-off decisions (and the valuations they imply) to be accumulated and compared. It would allow the true value of land to be assessed in a consistent and relatively inexpensive way. This will ultimately allow humanity to manage the earth's land sustainably and well.

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Appendix A: Data Sources Overview

Categories	Variables	Scale (spatial/non-spatial)	Database/URL
		Biophysical	
Climate	Mean maximum and minimum temperatures, precipitation, solar radiation (crop modelling needs may require more)	Global (GIS) National from individual weather stations (daily and monthly)	http://cru.uea.ac.uk WorldClim.org UN's FAO GAEZ Datasets http://fao.org/nr/gaez/en Evapotranspiration http://csi.cgiar.org/Aridity
Soils	Soil type and properties, existing soil degradation states, and soil quality/constraint	National and Global (GIS)	UN's FAO GAEZ Datasets: http://fao.org/nr/gaez/en Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/HWSD_Data.html?sb=4) http://isric.org/data/data-download

			http://africasoils.net Fractional land-cover (at global scale): using the bare soil component to detect possible soil erosion: See product already available for Australia here: http://data.auscover.org.au/xwiki/bin/view/Product+pages/Fractional+Cover+MODIS+CLW
Biomass productivity	Human-induced long-term NDVI trend	Global (GIS)	Oak Ridge National Laboratory DAAC: http://daac.ornl.gov/NPP/npp_home.shtml Global inventory: http://glcf.umd.edu/data/gimms NASA MODIS vegetation indices: MOD13Q1 (at 250m pixel) GLADA/GLADIS: Desertification: http://dis-nrd.uniss.it/index.php NASA Albedo at global scale: MCD43A3 (~500m) Fractional land-cover, now being developed at Global scale: to detect photosynthetic and non-photosynthetic vegetation. See product already available for Australia here: http://data.auscover.org.au/xwiki/bin/view/Product+pages/Fractional+Cover+MODIS+CLW
Land use			Land use: http://glcn.org/ont_1_en.jsp ALUM
Carbon sequestration and storage	Forest cover – gain – loss – or forest that haven't changed in the period 2000-2012	Global (GIS) based on Landsat TM	http://earthenginepartners.appspot.com/science-2013-global-forest 3D Land mapping (NASA) to detect old growth forest (Carbon sinks): http://lidarradar.jpl.nasa.gov
Agro-ecological	Agro-ecological zones, farming systems, length of growing period, existing land cover and land use maps, topography	National and Global GIS	UN's FAO GAEZ Datasets: http://fao.org/nr/gaez/en Elevation models: http://yale.edu/ceo/Documentation/dem.html http://cgiar-csi.org/data/srtm-90m-digitalelevation-database-v4-1 different OECD indicators of state of environment and agriculture: http://oecd.org/agr/env/indicators.ht

			m http://oecd-ilibrary.org/agriculture-and-food/oecd-compendium-of-agri-environmental-indicators_9789264186217-en Global Biodiversity Information Facility http://gbif.org
ES	Land cover(biome), LAI, benefit transfer		European Space Agency GlobCover Dataset: http://due.esrin.esa.int/globcover NASA MODIS Land cover dynamics: MCD12Q2 (at ~5600 m); MCD12Q2 (~500m) Global land cover: GlobCover. Ecosystem Services Value Database (ESVD): http://fsd.nl/esp/80763/5/0/50 The Environmental Valuation Reference Inventory™ (EVRI™): https://evri.ca/Global/Splash.aspx WAVES: /http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/ENVIRONMENT/0,,contentMDK:23124612_pagePK:148956_piPK:216618_theSitePK:244381,00.htmlS
Experimental data for crop modelling	As per software needs, numerous	Plot-level	???
Economic			
Socio-economic characteristics	Income per capita, population density, poverty rates, infant mortality rates, etc., Household demographic characteristics, income (farm and non-farm) and detailed expenses, asset ownership, physical and social capital, education levels, etc.	Sub-national, national and household level	Standard National Statistics from World Bank: http://data.worldbank.org/about/data-overview Human development factors: http://hdr.undp.org/en/data/api Summarized: http://quandl.com Oak Ridge National Laboratory LandScan Global Population Density Data: http://web.ornl.gov/sci/landscan Built Capital using Nighttime Lights: http://ngdc.noaa.gov/eog/download.html

Agricultural production	Crop areas and yields, input use: seeds, fertilizers, chemicals, manure, water, labor, farm machinery, fuel, others, Farm characteristics, livestock ownership, output marketing, previous land use changes	Household district and national	CIESIN Socioeconomic Data and Applications Center (SEDAC): http://sedac.ciesin.columbia.edu/data/collection/fertilizer-and-manure.html UN's FAO GAEZ Datasets: http://fao.org/nr/gaez/en Ray, D.K. et al. Recent patterns of crop yield growth and stagnation. Nat. Commun. 3:1293 doi: 10.1038/ncomms2296 (2012).
Prices	Output and input prices, land values when available	Sub-national and national (time series), Purchased input and marketed output prices at household level	FAO Stats: http://faostat3.fao.org/ OECD main economic indicators: http://stats.oecd.org/mei LandMatrix: http://landmatrix.org/en
Institutional			
Institutional	Market access, access to extension and information, access to credit, road density, night time lighting intensity series, land tenure, Government effectiveness, household risk attitudes from field experiments, membership in associations	National and household	Oak Ridge National Laboratory Landscan Global Population Density Data: http://web.ornl.gov/sci/landscan Built Capital using Nighttime Lights: http://ngdc.noaa.gov/eog/download.html Open Street Map: http://openstreetmap.org/#map=4/38.01/-95.84 National borders: http://gadm.org/ http://infrastructureafrica.afdb.org/models/irrigation.asp Mobile phone use/availability: http://itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx? Land Tenure: http://wri.org/map/status-land-tenure-andproperty-rights-2005 FAO: http://fao.org/gender/landrights/home/en/Government effectiveness: http://govindicators.org World Development Indicators: http://worldbank.org Human development index: http://data.undp.org Trust:

			http://wvsevsdb.com/wvs/WVSIntegratedEVSWVS.jsp?Idioma=I Homicide rate(global map, national level):http://unodc.org/unodc/en/frontpage/unodc-releases-global-homicide-data.html Global network coverage map: http://submarinecablemap.com/ Flight connectivity: http://openflights.org/data.html http://transtats.bts.gov
SLM practices			
SLM practices	Knowledge and use of SLM practices, sources of knowledge, perceived constraints on SLM adoption	Household	FAO AQUASTAT: http://fao.org/nr/water/aquastat/investment/index.stm WOCAT: http://WOCAT.com Environmental performance of agriculture: http://oecd.org/greengrowth/sustainable-agriculture/1890358.htm GRN: http://globalrestorationnetwork.org/database
SLM policies	National policies having impact on land degradation and SLM: subsidies and taxes, land use planning and production quotas, export and import tariffs, barriers and quotas, etc.	National	National environmental performance index: http://epi.yale.edu Environmental policy and indicators: http://eea.europa.eu/data-and-maps/indicators/#c5=&c7=all&c0=10&b_start=0; http://www2.oecd.org/ecoinst/queries/Default.aspx
Indirect use, non-use, and off-site values	Obtained from literature, whenever possible, own data collection and estimation	Sub-national, national and global	Stakeholder interviews: http://kcl.ac.uk/projects/desertlinks/indicator_system/mandata/mandata.htm