

## Challenges for land system science

Mark D.A. Rounsevell<sup>a,\*</sup>, Bas Pedrolí<sup>b</sup>, Karl-Heinz Erb<sup>c</sup>, Marc Gramberger<sup>d</sup>, Anne Gravsholt Busck<sup>e</sup>, Helmut Haberl<sup>c</sup>, Søren Kristensen<sup>e</sup>, Tobias Kuemmerle<sup>f,j</sup>, Sandra Lavorel<sup>g</sup>, Marcus Lindner<sup>h</sup>, Hermann Lotze-Campen<sup>j</sup>, Marc J. Metzger<sup>a</sup>, David Murray-Rust<sup>a</sup>, Alexander Popp<sup>j</sup>, Marta Pérez-Soba<sup>b</sup>, Anette Reenberg<sup>e</sup>, Angheluta Vadineanu<sup>k</sup>, Peter H. Verburg<sup>l</sup>, Bernhard Wolfslehner<sup>i</sup>

<sup>a</sup> School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK

<sup>b</sup> Alterra, Wageningen UR, P.O. Box 47, NL-6700 AA Wageningen, The Netherlands

<sup>c</sup> Institute of Social Ecology Vienna (SEC), Alpen-Adria Universität Klagenfurt, Wien, Graz, Schottenfeldgasse 29, 1070 Vienna, Austria

<sup>d</sup> Prospex bvba, Vluggestel 6, B-3140 Keerbergen, Belgium

<sup>e</sup> Department of Geography and Geology, University of Copenhagen, Oster Voldgade 10, 1350 Copenhagen, Denmark

<sup>f</sup> Department of Geography, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

<sup>g</sup> Laboratoire d'Ecologie Alpine, CNRS UMR 5553, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France

<sup>h</sup> European Forest Institute, Torikatu 34, 00100 Joensuu, Finland

<sup>i</sup> European Forest Institute, Regional Office for Central Eastern Europe, c/o University of Natural Resources and Life Sciences, Vienna, 1180 Vienna, Austria

<sup>j</sup> Potsdam Institute for Climate Impact Research (PIK), PO Box 601203, 14412 Potsdam, Germany

<sup>k</sup> Department of Systems Ecology and Sustainability, University of Bucharest, Spl. Independentei 91-95, Bucharest, Romania

<sup>l</sup> Institute for Environmental Sciences, VU University Amsterdam, De Boelelaan 1087, 1081HV Amsterdam, The Netherlands

### ARTICLE INFO

#### Article history:

Received 25 July 2011

Received in revised form 9 January 2012

Accepted 12 January 2012

#### Keywords:

Land system science  
Environmental change  
Scenarios  
Land use modelling

### ABSTRACT

While considerable progress has been made in understanding land use change, land system science continues to face a number of grand challenges. This paper discusses these challenges with a focus on empirical land system studies, land system modelling and the analysis of future visions of land system change. Contemporary landscapes are contingent outcomes of past and present patterns, processes and decisions. Thus, empirical analysis of past and present land-use change has an important role in providing insights into the socio-economic and ecological processes that shape land use transitions. This is especially important with respect to gradual versus rapid land system dynamics and in understanding changes in land use intensity. Combining the strengths of empirical analysis with multi-scale modelling will lead to new insights into the processes driving land system change. New modelling methods that combine complex systems thinking at a local level with macro-level economic analysis of the land system would reconcile the multi-scale dynamics currently encapsulated in bottom-up and top-down modelling approaches. Developments in land use futures analysis could focus on integrating explorative scenarios that reflect possible outcomes with normative visions that identify desired outcomes. Such an approach would benefit from the broad and in-depth involvement of stakeholders in order to link scientific findings to political and societal decision-making culminating in a set of key choices and consequences. Land system models have an important role in supporting future land use policy, but model outputs require scientific interpretation rather than being presented as predictions. The future of land system science is strongly dependent on the research community's capacity to bring together the elements of research discussed in the paper, via empirical data collection and analysis of observed processes, computer simulation across scale levels and futures analysis of alternative, normative visions through stakeholder engagement.

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### Introduction

The land system is central to understanding the relationship between people and their environment (Reenberg, 2006). The sustainable provision of goods and services critically on

managing land resources without damaging the natural resource base (MA, 2005). To support the transition towards sustainable development, science needs to better understand how land use change affects the environment and how this, in turn, feeds back into human livelihood strategies or influences the vulnerability of people and places (Foley et al., 2005; Lambin et al., 2006; Turner et al., 2007).

Significant progress has been made in deepening understanding of the land system over the last few decades (Reenberg, 2009)

\* Corresponding author.

E-mail address: [mark.rounsevell@ed.ac.uk](mailto:mark.rounsevell@ed.ac.uk) (M.D.A. Rounsevell).

promoted by 'The Global Change and Terrestrial Ecosystem' and 'Land Use Land Cover Change' (GCTE-LUCC) communities under the IGBP and IHDP programmes (Canadell et al., 2007; Lambin et al., 1999; Lambin and Geist, 2006). Research conducted in the LUCC programme demonstrated the pivotal role of land change in the Earth system and helped the international research community to greatly increase its understanding of the dynamics of land use change and its consequences. The Global Land Project (GLP, 2005) has continued the work of LUCC, and in doing so identified two major challenges in studying the links between human transformations of land systems and the changing role of land systems in Earth System functioning: (a) improving our understanding of the complex feedbacks between the societal and environmental components of the integrated land system, and (b) up-scaling of local and regional process understanding to achieve global process understanding (GLP, 2005).

Interactions between decision-making, governance structures, production and consumption, technology, ecosystem services and global environmental change influence human activities at the local and regional scale, and are influenced by and feed back to the global scale, thereby shaping trajectories of human–environment interaction in land systems (Lambin and Meyfroidt, 2011). Land system research therefore has to cope with the substantial challenge of multi- and inter-disciplinarity to bridge the nature-society divide (Bloemers et al., 2010; Latour, 1991; McNeill, 1995). We are now in a position to understand some of the multidisciplinary issues affecting land system science including: the behaviour of people and society (agents and structure), the multi-level character of both decision makers and land units, the ways in which people and land units are connected to the broader world within which they exist, and the aspect of time, both past and future (Lambin et al., 2006).

In spite of recent progress in understanding the human and biophysical processes that influence land systems, a number of grand challenges remain for land system science. Land system science refers to the "... interdisciplinary field [that] seeks to understand the dynamics of land cover and land use as a coupled human–environment system to address theory, concepts, models, and applications relevant to environmental and societal problems, including the intersection of the two" (Turner et al., 2007). This paper discusses the challenges for land system science by taking stock of current knowledge about land system dynamics, and uses this as the basis for a discussion about where land system science may go in the future using integrated and interdisciplinary approaches. The paper is structured around a set of key methodological questions that have emerged from recent progress within land system science:

- (1) How can the analysis of empirical and historical land system datasets provide insight into human–environment interactions?
- (2) How can integrated modelling and the ecosystem service concept contribute to the testing of hypotheses about land system functioning and decision making?
- (3) How can our current understanding of land systems inform the choices that society has about future landscapes?

In the following, we explore each of these questions by reviewing the current state-of-the-art in land system science and discussing the challenges for the future of land system research. We also present our visions about how to deal with the grand challenges for land system science.

### State-of-the-art in land system science

#### *Empirical analysis of human–environment interactions*

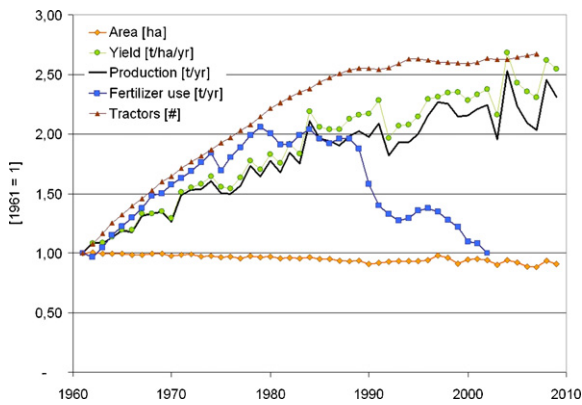
The expanding fields of environmental history and long-term socio-ecological research (LTSER) (Collins et al., 2011; Haberl et al.,

2006; Redman et al., 2004) provide opportunities to bridge the gap between the natural and social sciences, and to better understand the human dimensions of global change. The development of contextualised histories that are explicit in recognising layered scales of analysis in both time and in space can highlight the complexity of specific local geographical and historical settings (Haberl and Krausmann, 2007). This opens up the possibility of reinterpreting and redefining baseline conditions to identify, for example, the importance of disturbance regimes for vegetation dynamics across broad geographic regions (e.g. Batterbury and Bebbington, 1998; Dearing et al., 2010; Ellis et al., 2010; Klein Goldewijk et al., 2011; Pongratz et al., 2008). Interactions within coupled human–environment systems comprise, amongst others, changes in land use practices, associated changes in land cover (e.g. de- and afforestation) and changes in climate and CO<sub>2</sub> fluxes between the land surface and the atmosphere, as well as the potential effects of global environmental change on agriculture, food, fibre and biomass production and consumption, food quality and security, and ecosystem functioning (e.g. Gallopín, 2006; Haberl et al., 2001a,b; Lambin et al., 2003; Mooney et al., 2009; Steffen and Tyson, 2001).

Land use change over time has been a critical factor in the creation of landscapes and environmental conditions over large areas (Foley et al., 2005; Gutmann et al., 2005). While being dependent on biophysical conditions, human use of the land results in significant changes to these conditions, with human activities largely shaping or even controlling a significant proportion of the biophysical patterns and processes within most landscapes. Land cover is co-determined by natural and socio-economic factors and their interaction (Berglund, 1991; Buttner, 2001; Farina, 2000; Kristensen et al., 2009; Pedroli et al., 2007). Current approaches in land use science based on the characterisation and analysis of biophysical parameters using remote sensing are not sufficient to develop a comprehensive understanding of changes in the socio-economic functions of land (Ellis and Ramankutty, 2008; Verburg et al., 2009). Thus, the role of biophysical processes and the socio-economic flows of materials and energy are critical for analysing and understanding trajectories of land use change (Krausmann et al., 2003). Furthermore, it is important for studies of land system change to address the cultural aspects of landscape patterns (Ramakrishnan et al., 1998; Tuan, 1968) and the effect of this on decision-making processes (Newig et al., 2008) as well as the institutions and governance structures involved in land management (Ostrom, 1996, 1999; Nagendra, 2007; Young et al., 2008).

As contemporary landscapes are contingent outcomes of past and present patterns, processes and decisions, the empirical analysis of past and present land use change has an important role in providing insights into the socio-economic and biophysical processes that shape land use transitions. Such analysis would benefit from exploring socio-economic and ecological interdependencies in the land system across spatial and temporal scales (Reenberg, 2006, 2009). Systematically linking socio-economic and biophysical drivers and trajectories is a prerequisite for the assessment of sustainable development (Fischer-Kowalski and Haberl, 2007; Fischer-Kowalski and Rotmans, 2009). Changes in socio-ecological metabolism (material and energy flows in human and natural systems), land-use change, changes in governance and communication processes have been identified as major research themes in LTSER (Haberl et al., 2006). While these systemic interdependencies are, in principle, increasingly recognised, the specific interdependencies in space and time between decision-making processes for different scales, institutional structures, socio-economic contexts and land-system patterns are poorly understood.

Much of the recent land change science has focused on mapping land cover conversions brought about by land use change (e.g. deforestation), motivated by rapid development in remote-sensing



**Fig. 1.** Change in cereal production, cropped area and yield and the trends in fertilizer application and agricultural machinery use in the EU-27 countries from 1961 to 2009. Whereas the extent of cereal cultivation decreased over this period, cereal production more than doubled, due to yield increases of a similar magnitude. Thus, production increases cannot be explained on the basis of simple relationships between agricultural inputs and output: whereas mechanisation closely follows the production dynamics, the development of fertilizer use over time follows a completely different direction. Understanding of the mechanisms underlying these dynamics is still limited.

Source: FAOstat, online; data indexed to the year 1961.

technologies, the availability of satellite images and increasing computational capacity. Despite these developments, the identification of dynamics in land management that are not reflected in land cover changes, but which strongly affect socio-economic inputs, as well as outcomes and ecological effects, remains a challenge. Of particular interest is the process of agricultural land use intensification, although this is only part of a wider more complex set of land use change processes. Global cereal output increased by a factor >2.5 times from 1961, whereas the area devoted to cereal cropping has remained largely stable. This suggests that almost all of the additional cereal produced globally came from the intensification of production and very little from expanding crop areas. This change was achieved through massive technological development (such as crop breeding), cropping intensity, input of fertilizers and pesticides and the use of machinery and irrigation (Alston et al., 2009; IAASTD, 2009). Fig. 1 provides an example of cereal yield changes for the European Union.

Despite considerable research efforts to improve our understanding of agricultural intensification (Bakker et al., 2007; Boserup, 1965, 1981; Foley et al., 2005; Lambin et al., 2000; Rudel et al., 2009), the concept is inadequately defined and generic analysis of the change processes are therefore lacking. There are many different definitions of intensification, some of which refer to increases in inputs (e.g., energy, fertilizer or water), increased outputs (e.g., yields per unit area and year) or management practices (crop rotation, fallow, cropping intensity, etc.). While some stress the negative environmental impacts of intensification resulting, amongst others, from nutrient leaching, soil degradation, biodiversity loss of intensively cultivated areas (e.g., IAASTD, 2009), others highlight the positive environmental effects of potential land-saving, intensive cultivation technologies (e.g. Burney et al., 2010; Phalan et al., 2011). Increasing the empirical basis as well as developing innovative methods (e.g. biophysical indicators capable of measuring and mapping land use intensification and extensification on ratio scales that complement nominal scales currently used in most land-change research) is required to advance these lines of inquiry (Erb et al., 2009; Temme and Verburg, 2011).

#### Modelling land system dynamics

Models have played a major role in land system science in undertaking structured analysis of complex interactions within the land

system. Where real-life experiments are not possible, models provide artificial experiments to explore system behaviour, i.e. as a computational laboratory (Matthews et al., 2007). In addition, models enable ex-ante assessments of policies and provide input to the planning process (Bennett et al., 2003; Helming et al., 2011a,b; Nilsson et al., 2009; Nowicki et al., 2008; Rounsevell et al., 2006; van Ittersum et al., 2008). Future land use will be strongly determined by policy changes such as reforms in agricultural policy, trade liberalisation and nature conservation, but also by fundamental changes in energy policy and new measures that relate to climate change adaptation and mitigation (Beringer et al., 2011; Lotze-Campen et al., 2010; Popp et al., 2010; Rounsevell and Reay, 2009). For example, the European Commission demonstrated the importance of climate change for future policy directions by establishing a new Directorate-General for Climate Action (“DG CLIMA”) in 2010.

Yet, modelling efforts have focussed on specific aspects of the land system with much ex-ante analysis based on the agricultural sector using models of the agricultural economy (e.g. Britz et al., 2002; Rounsevell et al., 2003). Other models have targeted urbanisation processes (e.g. Petrov et al., 2009; Reginster and Rounsevell, 2006). At the case study level, models of human decision making (e.g. agent based models) have been developed, but these are seldom applied in a policy and planning context (Parker et al., 2002; Matthews et al., 2007; Verburg et al., 2006a,b) with limited exceptions (Gaube et al., 2009). The focus on either top-down (multi-)sectoral approaches or bottom-up, agent-based approaches does not sufficiently capture the complexity of human–environment interactions across different scales. The further development of models for integrated analysis of human–biophysical causal relationships would benefit from combining data with different spatial scales and from widely different sources (e.g. Crawford et al., 2005; Gaube et al., 2009; Turner et al., 2007; Walsh and Crews-Meyer, 2002).

The macro-level context of local decision making is commonly captured in land system science with large scale macro-economic or integrated assessment models (Heisterman et al., 2006; Britz et al., 2002; Lotze-Campen et al., 2008). Accounting for the global context is important, as local and regional demands can be met in spatially unconnected regions through international trade (Dore et al., 1997; Lofdahl, 1998; Lotze-Campen et al., 2010). While these models have proven capable of addressing land change (Verburg et al., 2008; Van Meijl et al., 2006) the inherent characteristics and detailed processes of the land system are largely ignored by a high level of simplification.

Economic models (e.g. Hertel, 1997; Kuhn, 2003; Lee et al., 2005) can address the links between demand, supply and trade via endogenous price mechanisms. However, they account only to a limited extent for physical resource constraints, they do not commonly reflect the impact of demand on actual land-use change processes, and they rarely represent human behaviour not reflected through price mechanisms. Land is usually implemented as a constraint in the production of land-intensive commodities, and economic competition of different types of production within one sector is represented endogenously. The simulation of management types as well as the competition for land (and water) between different sectors is supported by the structure of such models, but only at a spatially aggregated level.

A range of different strategies exist to project future land-use patterns from regional to global scales. Geographic approaches (e.g. Van Delden et al., 2007; Verburg et al., 1999; Verburg and Overmars, 2009), concentrate on the supply side and compute land-use patterns based on spatially explicit data on land suitability and on external assumptions about agricultural demand. These approaches are strong in capturing the spatial determination of land use and its constraints based on land resources. However, they

lack the potential to treat the interplay between supply, demand, and trade endogenously. Furthermore, these models are mostly based on remote sensing data of land cover and therefore ignore changes in land management (Verburg et al., 2011). Changes in land management have more far-reaching consequences for the environment and human well-being than land cover change alone (Ellis and Ramankutty, 2008).

Integrated approaches, accounting for both socio-economic and environmental processes across different scales, pursue different strategies. Some employ land allocation schemes, which use demand or price information from economic models to update land-use patterns in detailed environmental models (e.g. Leimbach et al., 2012; Rounsevell et al., 2006; Tan et al., 2003). Others improve the representation of resource constraints in detailed economic models (e.g. Darwin, 1999; Rosegrant et al., 2002). The dynamic coupling of economic, integrated assessment and land use models has been used to address the trade-off between the spatial expansion of agricultural production and intensification at the global scale (Eickhout et al., 2007; Verburg et al., 2008).

Agent Based Modelling (ABM) provides a framework for simulating complex decision making (Bousquet and Page, 2004; Clifford, 2007; Janssen and Ostrom, 2006; Manson and Evans, 2007; Matthews et al., 2007; Parker et al., 2003). ABM originated in the computer sciences in the 1970s through artificial intelligence research (Hare and Deadman, 2004), but has recently gained popularity in the social sciences and is increasingly applied to land system change (Evans and Kelly, 2004; Gaube et al., 2009; Happe et al., 2006; Huigen, 2004; Parker et al., 2003). Early agent-based models (Hägerstrand, 1967; Schelling, 1971) were explicitly devised to have the simplest possible rules necessary to produce the desired behaviour. ABM has undergone an evolution towards increasingly complex and empirically grounded models (Janssen and Ostrom, 2006; Valbuena et al., 2009), used to produce results of increasing specificity. Only a very limited number of ABMs have attempted to do this for land system research and the development of these approaches further as part of a broader integrated modelling strategy would promote the progress in land system science enormously (Murray-Rust et al., 2011). Up-scaling of ABM applications to larger geographic regions would make model outputs relevant at the scales of analysis at which land management and policy plans are developed (Rounsevell et al., 2012). Up-scaling of ABM and integration with macro-level models has not previously been attempted.

Recent research has focussed on understanding the land system as a coupled human–environment system characterised by a variety of feedback mechanisms across different scales and path-dependencies, which provides the system with some degree of self-organisation (Brown et al., 2005; Manson and Evans, 2007; Rindfuss et al., 2008; Veldkamp, 2009; Verburg, 2006). New assessment methods that combine agent-based models with models based on macro-level economic analysis of the land system would in principle be able to reconcile the multi-scale dynamics currently encapsulated in bottom-up and top-down modelling approaches.

### The ecosystem service concept and evaluating trade-offs

Nature provides human society with a vast range of benefits such as food, fibre, clean water, healthy soil, carbon capture and many more. Our well-being depends entirely on the continuous provision of these ecosystem services (Daily, 1997; Daily et al., 2000; MA, 2005). Several recent studies have proposed to support policy, management and land planning by analysis of the spatial distribution of multiple ecosystem services at global (Naidoo et al., 2008), regional (Chan et al., 2006; Reyers et al., 2009; Willemsen et al., 2008) or landscape scales (Gimona and Van der

Horst, 2007; Naidoo and Ricketts, 2006). Such analysis could aid the understanding of drivers of multiple ecosystem service delivery (Bennett and Balvanera, 2007), the modelling of land system change (Verburg et al., 2009) and sustainable land use planning (Turner et al., 2007).

Most published studies of ecosystem service mapping make the fundamental assumption that land cover or land use can be mapped to ecosystem service values, i.e. a unique value for a given ecosystem service is assigned to a land use/land cover type and ecosystem services maps are directly derived from land use/cover maps (Burkhard et al., 2009). While there is value in such an approach, especially at large scales where information beyond land cover is lacking, this also limits the capability to understand mechanisms that affect ecosystem service delivery (Verburg et al., 2009; Locatelli et al., 2010). Ecosystem functioning may not be uniform across a land use/cover class due to biophysical drivers (e.g. topography, soil type) or management (e.g. agricultural inputs, grazing intensity, logging practices).

Another approach has been to apply biophysical models for different ecosystem functions, allowing projections of ecosystem services over ecosystem (raster) maps incorporating such effects (Metzger et al., 2008; Quétiér et al., 2009; Schröter et al., 2005). Increasing biophysical realism in ecosystem services model remains an essential challenge (Eigenbrod et al., 2010; Lavorel et al., 2011; Seppelt et al., 2011). The usability of ecosystem services for a given level of ecosystem functions may depend on economic or social factors, e.g. on distance to roads, farms or markets, access to water (Gimona and Van der Horst, 2007; Hein et al., 2006; Willemsen et al., 2008). Moreover, valuation of ecosystem service provision is strongly affected by the often conflicting goals and objectives of individuals or societal groups. Different stakeholder groups develop and express different preferences for the provision of goods and services from land use, and these preferences might also differ between services, sectors, and regions (Locatelli et al., 2010).

Trade-off analysis tries to capture and synthesise both the available scientific-empirical evidence and value information to make explicit the sources and mechanisms of potential conflict at different scales. There are various approaches to trade-off analysis of ecosystem services. Classical approaches have often been implemented through linear programming e.g., in biophysical and economic land-use analysis (Bouman et al., 1999). To integrate stakeholder perceptions and interests in a participatory process, multi-criteria analysis (MCA) methods have been successfully used (e.g. Brown et al., 2001; Janssen et al., 2007; Strager and Rosenberger, 2006). The integration of spatial aspects into MCA has been demonstrated inter alia in vulnerability assessment (Tran et al., 2004) and land conservation (Strager and Rosenberger, 2006). Spatial MCA provides a broader portfolio of analyses that view trade-offs not only amongst land-use patterns at different geographical scales and different time horizons from scenarios, but also amongst stakeholder interests and objectives (Bennett et al., 2003; Polasky et al., 2011). It is crucial that both a science-based quantification and a value-based evaluation are made in order to identify, consolidate and consider the subjective choices and tacit knowledge of stakeholders.

### Land system futures

Scenarios are used increasingly in environmental change assessment as a means of exploring uncertainties about the consequence of human actions on the environment (Rounsevell and Metzger, 2010) and as part of policy cycles (EEA, 2011). Much of this effort has been driven by concern about climate change, as an exemplar of human–environment interactions with the work of the Intergovernmental Panel on Climate Change (IPCC) notable (Nakicenovic

et al., 2000). Most foresight analysis methods in environmental change have used explorative storylines to provide scenarios of alternative plausible futures (MA, 2005; Rounsevell et al., 2006; Metzger et al., 2010). Although such studies provide insight into the magnitude and uncertainty of future changes, and can be used in 'strategic conversations' with stakeholders (van der Heijden, 2005) in an attempt to extract policy implications, they are often criticised by policy makers because they are not targeted at policy questions (Bryson et al., 2010) and fail to provide a framework for the analysis of trade-offs between competing societal and policy objectives (Da Costa and Werning, 2008).

Normative scenario methods, describing pathways to desired future outcomes, or visions, potentially have greater policy relevance (Rounsevell and Metzger, 2010). Such methods include backcasting, where pathways to desired end points are explored, e.g. to a specific policy objective, and more advanced road-mapping techniques, describing a sequence of measures designed to bring about a desirable future and overcome potential barriers. Roadmaps have been used in policy as a descriptive term for any collaborative foresight process of significant scale and scope (e.g. U.N.-led 'Roadmap for Peace' to resolve the Israeli-Palestinian conflict), and as policy advice by suggesting possible strategies to achieve a desired future, e.g. for the journey to a post-Kyoto protocol (Clemençon, 2008) or for technologies enabling future low-carbon energy production and consumption (International Energy Agency, IEA: [http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD\\_ID=4156](http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD_ID=4156)). In environmental assessments, normative scenarios have been used primarily in ex-ante policy evaluation (e.g. van Ittersum et al., 2008), or visionary studies with a strong emphasis on the benefits of desired states (e.g. a hydrogen based economy, (McDowall and Eames, 2006), ignoring the plausibility of the required development pathways. A further disadvantage of normative scenarios is that they often ignore uncertainties in the long-term future, e.g. those associated with climate change, which are expressed explicitly in traditional explorative approaches.

Structured roadmap techniques have not yet been developed or used in integrated resource management for land systems. Such approaches would benefit however from the integration of explorative scenarios that reflect possible land use futures with normative visions that identify desired land use futures.

## A way forward for land system science

### Principal research questions

In this section we discuss the way forward for land system science with respect to the key questions and knowledge gaps outlined above. Our approach seeks to develop insight into the observation and modelling of land system processes at multiple spatial and temporal scales. The close interaction with relevant decision makers at regional and national levels is crucial in order to enhance the evidence-based and problem-oriented science-policy interface. Structured approaches would benefit from incorporating the views of a broad set of stakeholders responsible for land use planning and natural resource management policies and decision-making, setting dynamic targets for sustainable ecosystem and resource management. This leads us to propose three major research questions:

1. Which innovative 'visions' can be formulated for future sustainable resource management and land use policy development under a range of environmental and management conditions?
2. What are the socio-economic and ecological 'processes' that shape land use transitions?

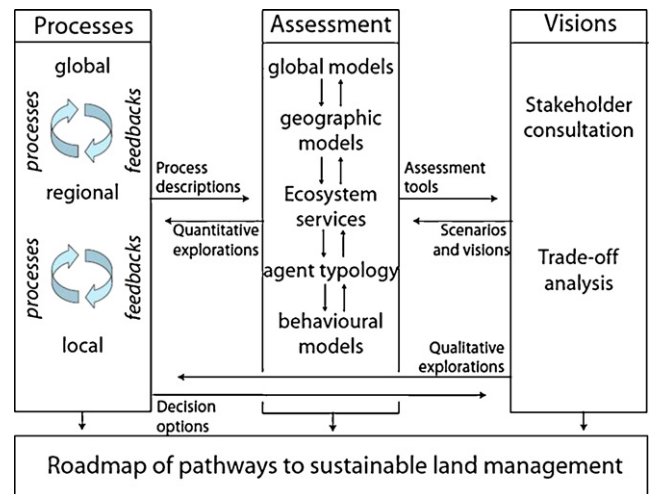


Fig. 2. An integrated methodological framework to assess land systems in the past, present and future.

3. How can bottom-up and top-down modelling tools be improved and used in a comprehensive 'assessment' of critical thresholds for resource management with reference to land use change and ecosystem services?

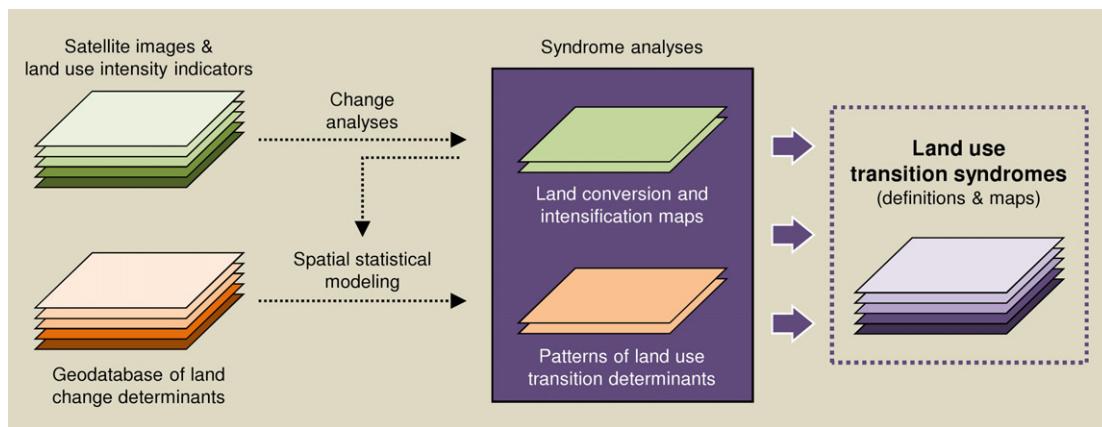
Tackling these research questions will help to better understand the interactions between future land-system change and socio-ecological sustainability. The relationships between these research questions are shown in Fig. 2. A prerequisite for future research is that it builds on the strengths of existing approaches and understanding to further insight into land system change. However, research on 'visions' could be used to narrow down the infinite spectrum of possible policy decisions to a bandwidth of relevant and sustainable land management options and choices. Research on 'processes' would analyse the empirical, evidence-base of land use change and the geographic variability of the processes that cause these changes. Research on 'assessment' using models is required to explore the dynamics and feedbacks across spatial and temporal scales in the identification of critical pathways for future land management.

### Challenges in developing visions and road maps

Roadmaps can be used to identify a range of alternative pathways that lead to sustainable land use futures that: (a) explicitly incorporate the uncertainties associated with long-term projections; and, (b) consider plausible and desired visions of future land use. Although the published literature on road mapping methodologies remains scarce (Kostoff and Schaller, 2001), and is focused primarily on technology roadmaps as a management tool for industry (Phaal et al., 2004), several common stages can be identified. The first stage consists of defining the scope and boundary conditions of the roadmap. The second stage is 'developmental' with a final stage, the 'follow-up', involving the roadmap being reviewed and eventually used to provide support for policy implementation.

Both the development of road-mapping methods and the resulting outcomes would be highly novel for land system research and futures analysis. Five major challenges would need to be overcome in achieving such an outcome:

- development and implementation of a scenario framework that links plausible visions of desired futures to numerical models that incorporate uncertainties about future projections;



**Fig. 3.** Land use transition syndromes (i.e., archetypal patterns) can be identified from maps of land change and the drivers of land use transitions using a combination of quantitative (e.g. clustering and multi-criteria analyses) and qualitative approaches.

- identification of the critical pathways to reach the desired outcomes;
- broad and in-depth stakeholder engagement on scenarios, visions, trade-offs and roadmap development;
- improvement of the current mapping methodologies to be able to analyse the trade-offs and synergies in the provision of all ecosystem services under alternative land management scenarios;
- definition of a roadmap for future land resource management that is explicit about policy recommendations.

Central to these challenges is the role of stakeholder engagement to gain understanding in the range of desired futures amongst diverse stakeholder groups, i.e. politicians, policymakers, NGO and business leaders with an interest in land use (including the natural environment) and the services it provides to society. While there are many examples of participatory approaches in scenario development (Nilsson et al., 2009; Volkery et al., 2008), these efforts were mostly focused on exploratory analyses of what could happen, rather than exploring ways to reach a desired endpoint. There is much to be gained, however, from combining exploratory and normative approaches in participatory processes in a way that strengthens their specific contributions to the definition of strategic choices. While some insight can be obtained through literature review and document analysis, structured stakeholder engagement is crucial to identify degrees of agreement and divergence between stakeholder groups. Achieving this requires the involvement of many stakeholders (>100) in an integrated series of in-depth, participatory sub-processes, although considerable challenges remain for effective stakeholder engagement in all socio-cultural contexts. Crowd sourcing methods may be useful in dealing with numerous stakeholders and for eliciting societal views about desired futures.

Quantitative methods can then be used to analyse synergies and trade-offs in alternative pathways that lead most closely to the desired futures. Such analyses can pinpoint a set of key land use decisions that will fundamentally influence land systems in the coming decades. Roadmaps can then be used to evaluate the consequences of these choices in space and time by explaining the underlying processes and identifying crucial decisions using an interpreted narrative. This will generate a scientifically rich, yet highly focussed, process for the support of decision making on future land use.

#### Challenges in empirical land change research

Empirical land change research needs a better conceptual understanding of decision-making processes, in particular those

in land management that drive local, regional and global changes in the land system. Likewise, feedbacks between the highly interlinked underlying ecological and socio-economic drivers and constraints are often poorly understood, especially regarding the roles and inter-linkages of different policy fields, growing global integration, socio-economic transformations, culture, gender disparities and their effects on the changing demand for ecosystem services.

Providing new insights into these issues will require the bridging of spatial scales, from the local to the global, as much as temporal scales, from long-term, often gradual changes to short-term rapid changes (Young et al., 2006). Moreover, meeting the challenges faced by land system science will depend on innovative methods to combine not only social and natural sciences, but also qualitative and quantitative approaches. Qualitative information about land manager values or preferences is crucial in understanding the links between drivers, decision processes and land change dynamics. Quantitative data and spatial information such as land use maps or yield statistics are necessary to detect and assess land system change, enable up-scaling of results, cross-regional comparisons and longitudinal analysis. These insights will be vital components that underpin research on land change models and futures analysis.

The collection and analysis of qualitative and quantitative information at the local scale in case studies is an important foundation of empirical research (Young et al., 2006). In particular, case studies facilitate the analysis of major drivers of current land system change, such as the extensification and intensification of agriculture, with a focus on the links between land manager decisions and the surrounding environment. Such studies can also assess the impact of land system change on ecosystem services in a contrasting range of different landscapes. For example, studying land change in different geographic contexts such as Alpine, peri-urban, post-socialist, and Mediterranean settings can shed light on the way land managers react to exogenous influences (policies and regulations as well as market forces and business opportunities). Such insights could be up-scaled to larger geographic areas as a means of generalising about the range of land system processes at regional scales and for analysing the intended and unintended effects of different models of land use policy on sustainable land management. Such up-scaling needs to address 'scalar dynamics', i.e. the fact that processes may move at different speed, or even in different directions, at different spatial scale levels (Gibson et al., 2000).

Studying land systems at broader scales provides opportunities to understand the spatial patterns of land use transitions, to unravel non-stationarity in the drivers of land system change, and to reveal

'teleconnections' between countries and regions (Reenberg and Primdahl, 2009). This can be achieved by establishing explicit links between models of macro-economic dynamics, technological change and international trade with models of local land use allocation, land management and heterogeneous biophysical conditions (Leimbach et al., 2012).

Land change mapping has also focussed much on land conversions, while land use intensity changes, that may represent the bulk of land change in many regions worldwide (Asner et al., 2005; Erb et al., 2009; Rudel et al., 2009), remain poorly understood. However, methodological advances are being made to quantify land use intensity changes directly from satellite images (Kuemmerle et al., 2009; Röder et al., 2008). Moreover, analysing remotely sensed data in concert with land use statistics, for example using disaggregation approaches, is promising for the new insights this may provide into land use intensity change (Siebert et al., 2005; Erb et al., 2007; Neumann et al., 2009; Temme and Verburg, 2011). Finally, linking land-use and land-cover patterns with material and energy flows is an approach that can help to better understand land-use intensity by mapping the human appropriation of net primary production (HANPP) (Haberl et al., 2007), link production and consumption ('teleconnections') across space in a spatially explicit manner (Erb et al., 2009; Haberl et al., 2009) and better understand contentious issues such as the global bioenergy potential (Haberl et al., 2010).

A major challenge for land system science lies in identifying generic, archetypal patterns of land use transitions. The syndromes approach (Fig. 3) describes dynamic patterns within human–environment systems based on the premise that system change is due to a few high-level causes, resulting in a limited number of general outcomes (Petschel-Held et al., 1999; Petschel-Held, 2004). The approach is a promising way of identifying archetypes of land use transitions (Geist et al., 2005; Hill et al., 2008), which could, for example, be defined to represent particular policy responses. Once mapped (based on current land use or potential future land use), syndromes are a powerful tool to inform policy with scientific evidence.

#### *Challenges in land system modelling*

Developments in land system modelling can: (a) lead to a better understanding of the driving factors and critical processes underlying dynamics in the land system based on the use of quantitative methods and models; and, (b) assist in the design of an operational framework for the assessment and interpretation of land use futures using new understanding of land system change processes from empirical research. Land system models can provide important insights into land system functioning and functioning beyond the capacity of empirical methods through their ability to undertake experiments in virtual worlds that cannot be replicated in reality. At the same time, the representation of land use within models needs to be extended from a focus on (agricultural) land cover towards an evaluation of integrated land management futures.

Bottom-up land system models can provide information on the response and adaptive learning of agents to changing environmental and policy conditions, while top-down models can provide insight into the macro-scale variability of impacts and responses to changes in (international) markets and prices, investments, policies, and climate adaptation strategies. The combination, however, of bottom-up models and an integrated top-down approach to capture macro-level dynamics would improve representation and understanding of the interactions and critical feedbacks within the land system. Thus, an innovative coupling of a range of models would allow for the consistent analysis of the land system and its interactions as a whole. The multi-model approach makes use of the strengths of existing, individual land system models and,

at the same time, avoids the development of an unmanageably complex model with which to represent the whole system. Interaction between the top-down and bottom-up modelling approaches would lead to a more comprehensive representation of the land system. Multi-agent modelling in case studies would benefit from being informed by top-down models about the regional context under specific scenario conditions. Given that context, multi-agent modelling can then provide more detailed information about the local reaction of a land manager, which might be, for example, in response to changing levels of ecosystem service provision. At the same time, top-down assessments can be improved by using information from bottom-up assessments. Currently, most top-down models use generalised, uniform allocation mechanisms. However, human responses to scenario conditions and land management options differ greatly depending on the regional context, cultural history and other factors.

The development of a typology of responses based on the results of bottom-up models could be used to specify the allocation mechanisms for top-down models in a more context-dependent manner. Such an analytical framework would ensure consistency in land system responses across scales and sectors as well as making best use of the diversity of approaches available to address land system change. Fig. 4 provides an overview of how land system models might be integrated within a new modelling framework. Such multi-model frameworks are a feasible and powerful alternative to traditional integrated assessment models. Moreover, the explicit exchange of data and knowledge between different research groups and scientific disciplines within such a multi-model approach is highly valuable and leads to new insights into the functioning of the land system. Furthering the use of quantitative methods to explore the dynamics of the land system requires the design and implementation of a consistent framework for the assessment of alternative (policy) scenarios and land management options (e.g. see Helming and Pérez-Soba, 2011; Rounsevell et al., 2006; van Ittersum et al., 2008; Verburg et al., 2008).

Model-based simulations of the future need to be undertaken over time periods that incorporate the short-term for policy design and implementation as well as the mid- and long-term effects on the land system of global change drivers such as climate, social, economic and technological change. Some aspects of land system change can only be evaluated over longer time horizons, e.g. the impacts of climate change and climate-related policies and investments, but also ecological processes such as the regeneration of forests. To account for possible differential impacts on longer time scales, model-based assessments would also have to estimate long-term effects (approximately to the year 2100). The same models and assessment methods can be used for this purpose, but with more attention given to the global level interactions and feedbacks that affect the land system. Interpretation of these long term results can account for large uncertainties due both to scenario assumptions (Rounsevell and Metzger, 2010) and to the time period specific parameterisation of models.

Ecosystem services can be, amongst other things, measurable indicators of the different aspects of the functioning and change of the land system in which case they can provide an appropriate means for analysing and communicating results of quantitative land system assessments. Land system change in terms of ecosystem services can be quantified to indicate the effects on both commodity and non-commodity goods and services. There is currently a lack of coherent methods for assessing science- and value-based ecosystem service trade-offs and synergies such as land use functions (Paracchini et al., 2011) or MCA methods (Morris et al., 2011; Wolfslehner et al., 2011) that target stakeholder interactions for eliciting preferences and weights. The outcomes of such an analysis would be inter alia spatially explicit trade-off maps for land units, which support the identification of desired and

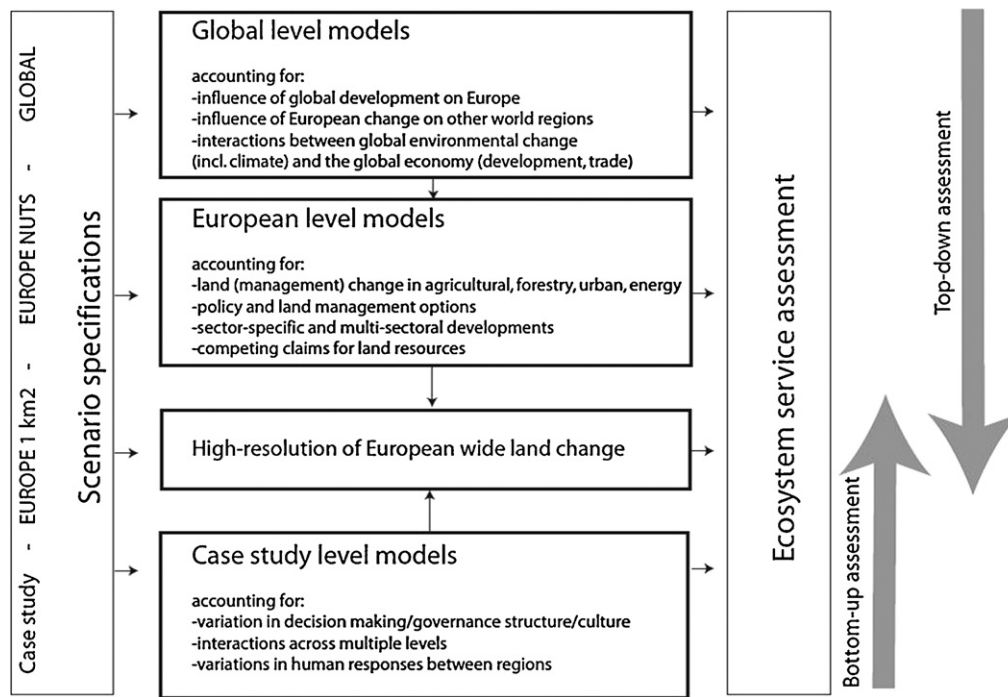


Fig. 4. Overview of an integrated modelling framework.

undesired consequences of land management decisions in terms of ecosystem services. Such an approach would not only explore outcomes, but also the causes and mechanisms of trade-offs in land use over a variety of different scales to allow the identification of responsive measures and management options.

### Discussion and perspectives

A key principle that has underpinned much of the thinking in land system research has been that observed patterns of land use and land use change can be used to infer the underlying processes that led to these patterns. In complex land systems, this principle does not hold. Many development pathways arising from multiple drivers and controlled by different processes can lead to the same land use patterns, while similar processes may lead to different patterns. This means that observations of patterns alone are insufficient to explain how or why a certain state emerged, only where. The paradigm shift in the thinking presented here is not to rely on observation alone, but to use both empirical analysis and model simulation in combination to explore the how and why of land system change. Models can be used to explore alternative development pathways, but models need to be grounded in, and able to reproduce, observation. The processes that models represent can only be informed by empirical evidence, yet observation alone cannot be used to explore the wide range of processes that occur in reality. The intention of coupling different land system methods is to exploit methodological strengths while overcoming their weaknesses. Such an approach aims to develop new and better insight into land system processes at a range of spatial and temporal scales in ways that can be used to infer how land systems might change in the future. This is a major challenge for the future of land system science.

All methods used in land system science are to some extent 'models' of reality (e.g. maps, scenarios and empirical data), not just the approaches to which this term is conventionally applied, i.e. computer simulation. The coupling of different models at different scale levels can provide new insights into the land system processes that play out at different scales. Again this includes

coupling of different empirical methods and computer simulation, as well as the coupling of computer models at different scales. This approach has considerable scope to inform policy processes that seek to manage land resources in a sustainable way. The capacity of models to generate large amounts of output in terms of mapped and graphical representations of many variables is, however, both a strength and weakness of the modelling method. Modelled outputs are seductive in their power to reflect land system change and are too often mistaken for the 'truth'. Using model outputs in a 'predictive' way and as an accurate representation of a land system has considerable risk. The outputs of models are better evaluated by the model developers in cooperation with stakeholders, so that erroneous interpretations and conclusions are not drawn. This becomes increasingly important as the complexity of models is enhanced through development and coupling across different scales. Moreover, it is now vital that future scientific approaches in land system science accommodate stakeholder participation in guiding sustainable development through a process of knowledge exchange. An important step here is the iteration between stakeholder input, model application and model outputs in order to integrate (land use) modelling results with value and preference information (Wolfslehner and Seidl, 2010). This requires careful planning and sequencing of the research agenda, involving stakeholders and modellers. How an appropriate level of knowledge exchange is achieved in practice and how this can support emerging policy agendas (e.g. see Bryson et al., 2010), requires more effort and innovative thinking by the land system science research community.

Developing sustainable multifunctional land-use strategies would benefit from building on a thorough understanding of how policies will affect land use and the land system goods and services. The biodiversity and renewable energy policies exemplify the point that land use policies can result in substantial trade-offs between different policy targets. On the other hand, there is also a possibility for synergies between, for example, biodiversity protection and enhanced biospheric carbon sinks as a measure to mitigate climate change (Díaz et al., 2009; Böttcher and Lindner, 2010; Hatanaka et al., 2011). Understanding trade-offs and synergies will be

essential in steering future land use towards wanted land system states while guarding against unsustainable thresholds of land use provisioning (Carpenter et al., 2009).

Several international conventions including the Convention on Biological Diversity (CBD) and the UN Framework Convention on Climate Change (UNFCCC) affect land use related policies, which will have strong influences on land systems. After failing in its policy target of halting the loss of biodiversity by 2010, the EU is now aiming “To halt the loss of biodiversity and the degradation of Ecosystem Services in the EU by 2020, restore them in so far as feasible, while stepping up the EU contribution to averting global biodiversity loss” (Environment Council Conclusions, 15th March 2010). As an effort to support emission reduction targets under the UNFCCC, the EU has set ambitious targets in the promotion of the use of energy from renewable sources including a binding target of 20% renewable energy in its overall energy mix by 2020. Achieving this target may result in a massive growth in energy production from biomass (e.g. European Biomass Action Plan (Com (2005) 628)). These policies are very likely to have considerable effects on natural resource management across a range of land use types. For example, implementing the ambitious renewable energy targets with a major share of woody biomass would result in significantly more intense biomass extraction from forest ecosystems, resulting in additional pressure on biodiversity protection (Verkerk et al., 2011), while the potential benefits for climate change mitigation are contentious (Searchinger et al., 2009).

## Conclusion

This paper addresses three pressing research questions pertinent to the sustainable management of land system change. In suggesting answers to these questions we identify major research gaps, but we also put forward views on the way forward for land system science. Providing insight into human–environment interactions is possible through integrated analysis of empirical and historical land system datasets, if empirical analysis and model simulation are used in combination to explore the drivers of land system change at a range of spatial and temporal scales. Integrated modelling based on the ecosystem service concept is expected to contribute substantially to the testing of hypotheses about land system functioning and decision making, assuming that iteration is undertaken between stakeholders, model applications and model outputs. The choices that society has about future landscapes can be informed in an innovative way through road-mapping and envisioning techniques that can guide future land use transitions. This will allow for the better definition of the bandwidth of both potential and desirable pathways of future land use change. There is growing awareness that the effectiveness of science in advising policy making can only be achieved through closer integration. This is especially true for land system research which aims to support policy making in the sustainable management of land resources because land plays a central and integrative role in many environmental decision processes from global to local scales. Sustainable land use strategies would benefit from being underpinned by a sound process understanding of how policies affect land use and ecosystem services and vice versa, and how the trade-offs and synergies between them work in practice. Embedding policy makers and relevant stakeholders in the research process through a carefully planned strategy of knowledge exchange, has the potential to support the formulation of sound, evidence-based policies. This paradigm shift in land system science requires a commitment to capacity building (mainly interdisciplinary and intra-disciplinary) that brings together the scientific and decision making communities. It offers a unique opportunity to bridge the gap between the

natural and social sciences with the aim of creating more sustainable land system management.

## Acknowledgements

The views expressed here were developed as part of the European Union funded VOLANTE project (FP7 Collaborative Project, grant agreement no. 265104; [www.volante-project.eu](http://www.volante-project.eu)). The research presented here contributes to the Global Land Project ([www.globallandproject.org](http://www.globallandproject.org)).

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