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Land Systems Modelling: An Atomistic Approach to Improve Handling of Complexity in Land-use and Land-cover Change Modelling

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Abstract: Improved understanding of land-use/land-cover change will be essential to help identify and follow more sustainable development pathways in a resource constrained world. While land-use/land-cover change models have advanced to address different domains, questions, processes, themes, scales and levels of complexity, they continue to have several inherent limitations. The limitations stem mainly from conceptualisation of landscapes as "scanned paper maps" that represent land use/cover as simple, non-overlapping categorical objects and include: 1) confounding of cover and use, 2) inability to depict more than one cover/use, 3) simplification of highly complex systems, 4) one process for many different types of change, and 5) substantial data pre-processing that hampers model development. To help overcome those limitations, we present a conceptual modelling approach that characterises landscape as "land systems" consisting of interacting components. Each component is depicted and operates at its own appropriate scale, subject to considerations of interest, data availability, or usually both. An important aspect is the atomisation of data into fundamental components or "elements." For example, an atomised land cover map results in a separate dataset for each land cover element. A common database stores all data atoms for possible re-use. Advantages include 1) scalability in space, time, and complexity, 2) extensibility such that data can be easily updated, replaced, added, or deleted, 3) depiction of multiple cover/uses/functions, and 4) fidelity between scale of process and scale of modelling. Disadvantages include 1) more substantial data requirements, 2) increased complexity of data storage and handling, and 3) lack of knowledge about many complex processes. We very briefly overview a conceptual framework of the land systems approach to the study of landscape change and its potential effects on ecosystem services.

Keywords*:* Complexity; land-cover change; land-use change; land systems.

1 INTRODUCTION

Land-use and land-cover change modelling is an important tool for studying coupled human-natural systems because it integrates the dynamics of human and biophysical systems [Agrawal et al. 2002]. Humans undertake activities that modify the biophysical aspects of landscapes (i.e. land cover) in particular ways to suit particular purposes (i.e. land use) [Di Gregorio 2008]. The interaction is bi-directional, as biophysical components of the landscape strongly influence where different human activities occur.

Given its ability to integrate human and natural systems, land-use and land-cover change modelling plays an important role in helping to explore a range of issues relating to the sustainable management of resources across a range of scales, such as urbanisation [Jantz et al. 2003], agriculture [Rounsevell et al. 2005], biodiversity [Reidsma et al. 2006] and ecosystem services [Metzger et al. 2006]. It is gaining increasing importance in global change studies, especially those related to climate change [Hurtt et al. 2011], and also increasingly serves as an organising mechanism to link models from different disciplines such as economics, ecology, hydrology, or soils [van Delden et al. 2011, Janssen et al. 2011].

While land-use/land-cover change models have advanced significantly to address different domains, questions, processes, themes, scales and levels of complexity [Rindfuss et al. 2004], they continue to have limitations related to the way in which land use and land cover is conceptualised and modelled [Verburg et al. 2009]. In this paper we discuss the typical limitations of land-use/land-cover conceptualisations and modelling, outline an approach to help overcome some of those limitations, and very briefly overview a conceptual approach to the study of the implications of land-use and land-cover change on ecosystem services.

2 LIMITATIONS OF EXISTING LAND-USE AND LAND-COVER CHANGE MODELLING

Many limitations of land-use/land-cover change modelling stem from the conceptualisation of landscapes as “scanned paper maps” that represent land use and/or land cover as non-overlapping categorical objects. This conceptualisation several inherent limitations for more complex modelling of human and/or natural dynamics including: 1) confounding of cover and use, 2) depiction of only one use or cover at any place, 3) oversimplification of complex systems, and 4) using one model to represent many processes and 5) substantial data pre-processing, which can hamper more rapid and expanded model development. Below we discuss each issue in more detail.

2.1 Confounding of Land Cover and Land Use

Many models of landscape change (but not all) confound land cover and land use, making it more difficult to model dynamics caused by human activities from those governed by biophysical or ecological processes. Land classes may, for example, include several categories of urban land uses (e.g., residential, industry, commercial) and several categories of land cover (e.g., forest, wetlands). The combination of cover and use is often a function of the available data. In New Zealand, for example, the national Land Cover Database contains a hybrid set of classes such as “high producing exotic grassland” or “exotic forestry” and often serves as the basis for land-*use* change studies as no official nationally-consistent and readily-available land-use database exists [Rutledge et al. 2009].

2.2 Inability to Depict More than One Use or Cover

The majority of landscape change models use non-overlapping categorical representations of land use and/or cover that allow for only a single land use or cover to occur at any place at any one time. This reduces the ability to characterise multiple land uses, which is more often the real situation, and therefore depict multiple functions across landscapes [Verburg et al. 2009].

2.3 Simplification of Highly Complex Systems

Categorical representations of land use or land cover represent simpler versions of more complex systems consisting of interacting biophysical components and human activities operating hierarchically across a range of scales. A simpler system representation may suit the particular purpose of the modelling. However simplified systems limit the number of possible states that can be explored and any associated dynamics and limit attempts to study more complex or subtle issues, such as impacts of land use intensification. Also categorical representations are often linked to a particular scale of depiction, whereas different human and natural systems inherently operate at different scales.

2.4 Single Process for Change

Many models have a single process for modelling transitions among different land classes. While a single process may serve for simple systems consisting of only a few landscape classes, increasing complexity increases the likelihood that different transitions may operate via different processes operating at different scales. Such considerations become critical when differentiating changes resulting from human versus non-human activities. For example vegetation clearance can result from human activity such as construction or via natural disturbance regimes such as storms. Also modelling multiple uses or multiple functions will likely require modelling multiple processes simultaneously, with each process operating at its own inherent scale as discussed above.

2.5 Pre-processing Slows Model Development

Preparing data needed for land-use/land-cover change modelling often requires substantial pre-processing that occurs independently from the modelling itself. Subsequent changes such as modifying the classification, altering factors driving change dynamics, or exploring different model structures can trigger the need for substantial re-processing before new data can be incorporated into the model or new model structures can be explored. As a result, model development time can increase substantially.

3 PROPOSED LAND SYSTEMS MODELLING FRAMEWORK

The increasing scope and complexity of resource management issues resulting from expected global trends and environmental limits [Alcamo and Leonard 2012,] generates increasing demand to accommodate more complexity in land-use and land-cover change modelling. Increased complexity would allow for a more realistic depiction of landscape conditions and a more complete understanding of the various change processes operating across landscapes, both individually and collectively. It would also allow for a fuller exploration of options for addressing pressing environmental issues across a range of scales [Barnovksy et al. 2012, Rindfuss et al. 2008].

To help overcome the limitations discussed above, we present a conceptual modelling approach that characterises landscapes as “land systems.” First we provide an overview of the land systems concept and second discuss its advantages and disadvantages in helping to overcome the limitations described.

3.1 Land Systems

A land systems model represents landscapes as a system i.e. as a set of interacting components. The concept follows on logically from the definition of an ecosystem, which is a set of interacting abiotic and biotic components [*sensu* Tansley 1935]. The simplest system has two components. For land-use/land-cover change modelling, a simple system would depict both use and cover separately (cf. figure 1a). A still conceptually simple but more complete land systems model would include climate, human activities, the built environment, vegetation, animals, and soils and landform (cf figure 1b). This model contains the basic components necessary to describe any ecosystem. Different combinations of components will then interact to generate a range of land uses, covers, services, functions, etc.

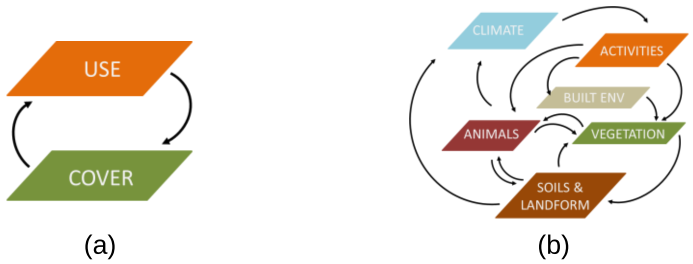

Figure 1. Two examples of conceptual land systems models. a) a simple 2-component model consisting of land use and land cover; b) a generalised land systems model.

A critical aspect of land systems modelling is the atomisation of data into fundamental "elements" represented by individual "atoms." For example, atomising a categorical land cover data layer with 20 land cover classes would result in 20 separate data elements. Each data atom represents a single instance of an element at a particular place and/or time, e.g. a patch of indigenous forest. Data atoms storage occurs in a common database (centralised or distributed) that the land-use/land cover change model can access directly. The land systems approach has a number of advantages and several disadvantages, both of which we describe below in more detail.

3.2 Advantages

3.2.1 Scalability

In a land systems model, system complexity scales according to the question of interest, data availability, or most commonly some combination of both. Scaling can occur spatially, temporally, or in terms of information. Because each data element is stored separately as data atoms, it becomes easier to combine different elements to characterise different landscape attributes or processes or, conversely, to characterise the same landscape differently. For example different organisations often classify land use to suit their individual purposes. Working from a common database, each organisation could recombine data elements as needed to produce their desired land-use classification. Data atoms also allow for flexible spatial or temporal scaling. Data atoms represented by polygons could be divided as needed or rasterised multiple times for depiction at finer scales for correspondence with elements at other scales. Similarly data atoms can be aggregated for depiction at coarser resolutions in different ways, e.g., percent of total area, count, or presence/absence. In practice the main limitation typically lies in the availability and resolution of the data atoms themselves.

3.2.2 Extensibility

Land systems models are highly extensible. They can be updated, simplified, or enhanced through the update, addition, replacement or deletion of data atoms and the relationships among them. This advantage becomes more important as more data accumulates, especially temporal data, and more complex models emerge. In a land systems approach data access also becomes more dynamic. For example if a model only requires a few cover classes, the individual data elements can be accessed directly, bypassing the need to manipulate the entire dataset. Information on relationships among data atoms that define the system(s) of interest are also stored to faciliate easier access and (re)processing to avoid or at least reduce the need for independent pre-processing as described earlier.

3.2.3 Depiction of Multiple Covers, Uses, Functions, and Processes

Land systems models can represent different combinations of covers, uses, functions or services across space and time, thereby addressing two of the limitations discussed above. First land cover and land use can be modelled separately. Also land cover or land use do not need to be modelled as categorical, non-overlapping representations. They can be described and modelled with as much or as little complexity as required. Agent-based modelling [Parker et al. 2003] already takes this approach by modelling agent behaviours and activities (i.e. land use) across landscapes (i.e. land cover). The flexibility of the land systems approach also means that complex representations of land use or land cover could be dynamically re-classifed into a simpler categorical classification if required, e.g., for input by another model or for reporting purposes by an organisation.

Second multiple dynamics of different uses, covers, functions and services can be modelled simultaneously and coupled in different ways to investigate the effects of different linkages and feedbacks. Different models can be developed and run concurrently to model different types of landscape transitions. This will hopefully lead to more insights into the actual processes of landscape change rather then generating alrorithms that are adept at replicating patterns of change.

3.2.4 Scale of Process and Scale of Modelling

In land systems modelling, different processes can be modelled at their inherent scale, provided the data atoms exist at the appropriate scale. Also processes operating across different scales can be more readily coupled to investigate hierarchical and/or more complex relationships.

3.3. Disadvantages

3.3.1 More substantial data requirements

Land systems modelling requires more data compared to typical land-use/land-cover change modelling. For each system component, a corresponding data element must exist. However in many cases, the required data may not be available, even for a simple land-use/land-cover model example such as in Figure 1a. More complex models will also likely require additional data that may not initially be available. While initially a disadvantage, over time we hope that the land systems approach will spur additional monitoring and data collection.

3.3.2 Increased complexity of data storage and handling

Taking a land systems approach increases data storage and handling complexity through the creation, storage and manipulation of data elements and the relationships among them. A typical land use or land cover data layer has the advantage that all the information occurs in one file such as a geospatial data layer. There is little overhead in storing or retrieving a single file, especially in terms of what the modeller has to remember. Atomising data can generate substantially more individual files, especially if a single data layer has many attributes, and increases the complexity of file management. For land system modelling to work effectively, more sophisticated data management and retrieval capabilities will need to be developed.

3.3.3 Lack of knowledge about many complex processes

We often lack adequate knowledge about the processes driving landscape change. Also common modelling practice advocates parsimony over complexity. Therefore, even if the required data exists, we may lack the knowledge or the impetus to construct more complex models. In that regard land systems modelling may remain a more aspirational concept for the foreseeable future. On the other hand increasing environmental pressures globally will demand more sophisticated modelling approaches if we wish to understand them adequately and address them successfully.

4 APPLICATION OF LAND SYSTEMS CONCEPT TO LANDSCAPE CHANGE AND ECOSYSTEM SERVICES

We are applying the land systems concept to the study of landscape change and ecosystem services in New Zealand. Below we overview the conceptual and technical approaches being undertaken to implement the land systems concept.

4.1 Conceptual Approach

Ecosystem services are the benefits that humans derive from ecosystems. Our framework conceptualises ecosystem services as functions of land systems (cf. figure 2). The set of services delivered depends on the various processes and functions of a particular land system, which consists of various components (climate, human activities subject to governance and tenure, various land cover elements, soils, landform) and their interactions (not explicitly shown). Land use is an emergent property of the land system. Typically human activities are undertaken to produce specific services such as food production, hence we also depict ecosystem services as an aspect of land use. Varying the components of the land system, such as human activity, will affect the suite of ecosystem services produced by altering the biophysical components of the system (climate, land cover, soils, landform). More complex representations of land use including multiple uses, functions or services, can be achieved by adding new components, new interactions or both.

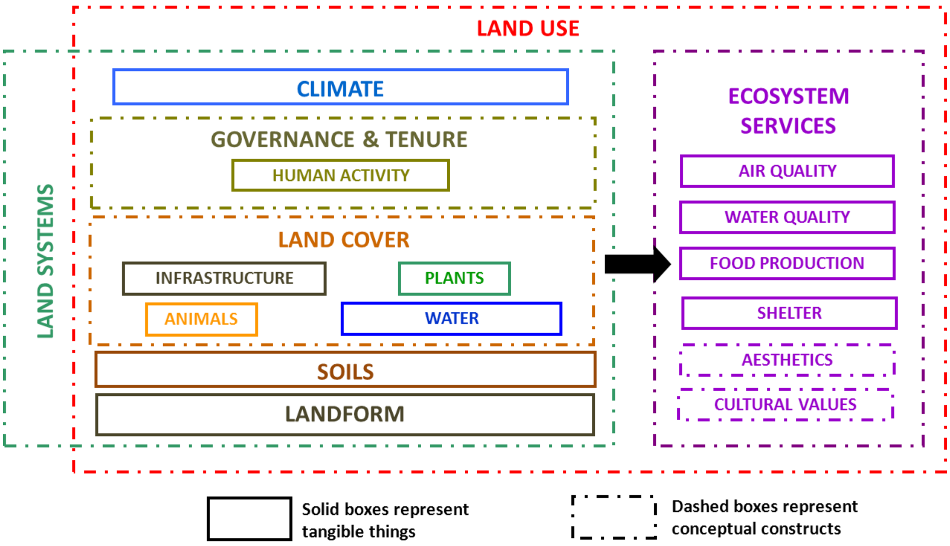

Figure 2. Conceptual approach to modelling the implications of land-use and land-cover change on ecosystem services.

4.2 Technical Approach

Implementing the land systems concept requires new approaches to data processing and manipulation and modelling. For data processing and manipulation, we have adapted a tool originally developed as an aid to land-use classification to process data for use in land systems modelling [Rutledge et al. 2011]. The tool stores rules for processing input data into data atoms, thus facilitating both rapid generation of new or updated data and sharing of methodologies. For the modelling environment, we are developing a general framework for dynamic raster-based modelling [Herzig 2012] that includes strong database-model coupling that the land system concept requires. The framework links an advanced raster database (rasdaman), image processing (Orfeo Toolbox, Insight Toolkit), input-output (GDAL), and graphical applications (QT, VTK Visualisation Toolkit) to facilitate the development of land systems models via advanced data storage, handling, processing, visualisation, and dissemination (e.g., via web services).

5 CONCLUSIONS

Land systems modelling represents an evolutionary step that will help overcome some limitations encountered in typical land-use/land-cover change modelling. By taking a systems approach, land use and land cover transform from simple categories with limited scalability and extensibility to more complex systems that can scale, expand/contract in scope and complexity, and interact dynamically. The increased flexibility creates opportunities for modelling multiple covers, uses and functions across landscapes in new and interesting ways. It also allows for multiple interpretations and realisations of the same data set to different degrees of complexity by specifying different interactions.

The increased flexibility arises because data is decomposed into its fundamental constituents or elements and stored as data atoms. The data atoms serve as building blocks that can be easily mixed and recombined to model different processes and functions at appropriate scales and rate. The approach offers the potential to help move land-use/land-cover change modelling further away from its historic roots in paper mapping and image analysis and transform it into a more rich, robust and useful tool for helping to address a growing list of pressing environment concerns and help design better systems to help anticipate early warning signs across global, national, regional and local scales [Barnosky et al. 2012].

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