Are agricultural land-use models able to predict changes in land-use intensity?

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Abstract

Land-use and land-cover change research needs to pay more attention to processes of land-cover modification, and especially to agricultural land intensification. The objective of this paper is to review the different modelling approaches that have been used in land-use/land-cover change research from the perspective of their utility for the study and prediction of changes in land-use intensification. After clarifying the main concepts used, the different modelling approaches that have been used to study land-use change are examined, case study evidence on processes and drivers of land-use intensification are discussed, and a conclusion is provided on the present ability to predict changes in land-use intensity. The analysis suggests there are differences in the capability of different modelling approaches to assess changing levels of intensification: dynamic, process-based simulation models appear to be better suited to predict changes in land-use intensity than empirical, stochastic or static optimisation models. However, some stochastic and optimisation methods may be useful in describing the decision-making processes that drive land management. Case study evidence highlight the uncertainties and surprises inherent in the processes of land-use intensification. This can both inform model development and reveal a wider range of possible futures than is evident from modelling alone. Case studies also highlight the importance of decision-making by land managers when facing a range of response options. Thus, the ability to model decision-making processes is probably more important in land-use intensification studies than the broad category of model used. For this reason, landscape change models operating at an aggregated level have not been used to predict intensification. In the future, an integrated approach to modelling — that is multidisciplinary and cross-sectoral combining elements of different modelling techniques — will probably best serve the objective of improving understanding of land-use change processes including intensification. This is because intensification is a function of the management of physical resources, within the context of the prevailing social and economic drivers. Some of the factors that should be considered when developing future land-use change models are: the geographic and socio-economic context of a particular study, the spatial scale and its influence on the modelling approach, temporal issues such as dynamic versus equilibrium models, thresholds and surprises associated with rapid changes, and system feedbacks. In industrialised regions, predicting land-use intensification requires a better handling of the links between the agriculture and forestry sectors to the energy sector, of technological innovation, and of the impact of agri-environment policies. For developing countries, better representation of urbanisation and its various impacts on land-use changes at rural-urban interfaces, of transport infrastructure and market change will be required. Given the impossibility of specific predictions of these driving forces, most of the modelling work will be aimed at scenario analysis. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Land-use and land-cover change, as one of the main driving forces of global environmental change, is central to the sustainable development debate. Land-use and land-cover changes have impacts on a wide range of environmental and landscape attributes including the quality of water, land and air resources, ecosystem processes and function, and the climate system itself through greenhouse gas fluxes and surface albedo effects. Whilst, a few years ago, most land-use and land-cover change research was focused on land-cover conversions (e.g., deforestation, urbanisation), researchers have increasingly realised that more subtle processes leading to a modification of land cover deserves greater attention. Land-cover modification is frequently caused by changes in the management of agricultural land use including, e.g., changes in levels of inputs and the effect of this on profitability or the periodicity of complex land-use trajectories, e.g., fallow cycles, rotation systems or secondary forest regrowth.

Agricultural land intensification has been one of the most significant forms of land-cover modification, with dramatic increases in yields being the main feature during the previous 30 years. Yields of food crops (per area of land) have outpaced global human population growth (Matson et al., 1997), but if current trends are extrapolated linearly into the future, intensification of agriculture will have major detrimental impacts on non-agricultural terrestrial and aquatic ecosystems (Tilman, 1999; Socolow, 1999). Intensification levels can also be an indicator of the ability of land-use systems to adapt to changing circumstances, e.g., because of policy or climate change. For example, many extensive land-use systems are marginal in productivity terms (e.g., uplands, semi-arid regions, high latitude areas, etc.) and these types of land uses often have little capacity to adapt. This does not follow, however, where extensive land use is a result of deliberate policy constraints on land that is not marginal in productivity terms. In this paper, it is contended, therefore, that land-use change research would benefit from a better understanding of the complex relationships between people and their management of land resources, and that land-use intensification is a vital consideration in these processes. This implies that, to fully understand and predict human impacts on terrestrial ecosystems, there is a need for more comprehensive theories of land-use change (Lambin, 1997, p. 389; Lambin et al., 1999, pp. 37–46, 89).

Much land-use/land-cover change research has been based on the use of models. Modelling, especially if done in a spatially-explicit, integrated and multi-scale manner, is an important technique for the exploration of alternative pathways into the future, for conducting experiments that test our understanding of key processes, and for describing the latter in quantitative terms. Many different modelling approaches have been adopted in the study of land-use/land-cover change, although most have been concerned with issues of land use conversion (Lambin, 1997; Kaimowitz and Angelsen, 1998). Few modelling studies have explicitly sought to evaluate potential changes in land-use intensification resulting from changes in management. Note, however, that economists have a long tradition in studying agricultural intensification in relation to management practices and conditions (e.g., prices of inputs, production functions). However, most studies have not revealed the driving factors, apart from economic incentives, that cause management to change. In this paper, the different modelling approaches that have been used in land-use/land-cover change research were examined from the perspective of their utility for the study and prediction of changes in land-use intensification. After clarifying the main concepts used, the different modelling approaches that have been used to study land-use changes are examined, case study evidence on processes and drivers of land-use intensification are discussed, and a conclusion is provided on the present ability to predict changes in land-use intensity.

2. Definitions

It is important to clarify terminology and definitions used in land-use/land-cover change research. Such terminology can be esoteric and, thus, affect the understanding of land-use/land-cover change research by a broad readership. The term land cover refers to the attributes of a part of the Earth’s land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures. Land use refers to the purposes for which humans exploit the land cover. Forest, e.g., is a type of land cover that is dominated by woody species and may be exploited
for land uses as varied as recreation, timber production or wildlife conservation. Furthermore, one may distinguish between land-cover conversion, i.e., the complete replacement of one cover type by another, and land-cover modification, i.e., more subtle changes that affect the character of the land cover without changing its overall classification (Turner et al., 1993).

The concept of intensification in land use often, although not exclusively, refers to agriculture. Agricultural intensification has been defined by Brookfield (1972) as the substitution of inputs of capital, labour and skills for land, so as to gain more production from a given area, use it more frequently, and hence make possible a greater concentration of production. Intensity is usually measured in terms of output per unit of land or, as a surrogate, input variables against constant land (Turner and Doolittle, 1978). Thus, one can distinguish between input intensification, which measures the increases in input variables, e.g., chemical fertiliser, pesticides, etc., and output intensification, which measures the increases in production against constant units of land area and time, e.g., food-tonnes or number of calories/hectare/number of years (Turner and Doolittle, 1978, p. 298). Because of data problems, surrogate measures are often employed (Kates et al., 1993, p. 12). Regardless of the measures and variables applied, any finding will vary from what is typically thought of as intensification since methods used in data gathering and analysis will strongly influence the relationship between variables. Conventional methods of measurement are, e.g., frequency of cultivation or number of harvests per plot over a standard time frame (after Boserup, 1965) as compared to, e.g., farm produce-generated income per hectare as a reflection of yields per hectare (Dorsey, 1999, p. 187).

Beginning at least with von Thünen in 1842, agricultural intensity (viewed in terms of production or yield per unit area and time) has long been regarded as a key concept in numerous explanations of agricultural growth and change (Turner et al., 1977; Turner and Doolittle, 1978). It had been pointed out by Kates et al. (1993, p. 21) that long-term population growth and economic development usually do not take place without intensification and agricultural growth, although intensification and agricultural growth do not inevitably follow population growth and are not necessarily beneficial or sustainable (see Mortimore (1993) for a review and a discussion of the theories of Boserup and neo-Malthusians).

3. Categories of land-use models

The modelling of land-cover change processes should aim to address at least one of the following questions:

1. Which environmental and cultural variables contribute most to an explanation of land-cover changes — why?
2. Which locations are affected by land-cover changes — where?
3. At what rate do land-cover changes progress — when?

Table 1 shows the four broad categories of land-use change models that may be used to address different questions, but which all require a different set of preliminary information: empirical–statistical, stochastic, optimisation and dynamic (process-based) simulation.

3.1. Empirical–statistical models

Empirical, statistical models attempt to identify explicitly the causes of land-cover changes using multivariate analyses of possible exogenous contributions to empirically-derived rates of changes. Multiple linear regression techniques are generally used for this purpose. The finding of a statistically significant association does not establish a causal relationship. Moreover, a regression model that fits well in the region of the variable space corresponding to the original data can perform poorly outside that region. Thus, regression models cannot be used for wide ranging extrapolations. Such models are only able to predict patterns of land-use changes which are represented in the calibration data set. Thus, these models are only suited to predict changes in land-use intensity where such changes have been measured over the recent past: in most studies this assumption is not valid. Note however that most empirical–statistical models are based on cross-sectional analysis of a series of farms, districts or counties. Because spatial variability in land-use systems is sometimes large, there will be, in some cases, empirical evidence of intensification. So, the derived regression model could be used to “predict” intensification of the observations lagging
Table 1
Categories of land-use change models

<table>
<thead>
<tr>
<th>What is already known on LUCC</th>
<th>What one needs to know on LUCC</th>
<th>Model category</th>
<th>Modelling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where and when in the past</td>
<td>When in the future (short-term)</td>
<td>Stochastic</td>
<td>Transition probability models</td>
</tr>
<tr>
<td>Where in the future (short-term)</td>
<td>Process-based, mechanistic</td>
<td>Behavioural models and dynamic simulation models</td>
<td></td>
</tr>
<tr>
<td>Why in the future (long-term)</td>
<td>Analytical, agent-based, economic</td>
<td>Dynamic spatial simulation models</td>
<td></td>
</tr>
<tr>
<td>Where, when and why in the past</td>
<td>Why in the future (underlying causes; scenarios)</td>
<td>Generalised von Thünen models</td>
<td></td>
</tr>
</tbody>
</table>

behind in the intensification process. Problems of causality do of course remain.

3.2. Stochastic models

Stochastic models which, for land-use change, consist mainly of transition probability models, describe stochastically, processes that move in a sequence of steps through a set of states. For land-use change, the states of the system are defined as the amount of land covered by various land uses. The transition probabilities can be statistically estimated from a sample of transitions occurring during some time interval. Probabilities of transitions are defined for changes from one land-cover category to another. Transition probability approaches are limited in their application to the question of land-use intensification because they only use transitions which have been observed in the recent past — which is similar to empirical–statistical models. However, some other forms of stochastic models, such as spatial diffusion models, do appear to be useful in research on intensification. Hägerstrand (1968) developed stochastic approaches based on Monte Carlo simulation to explain the diffusion of innovation through Swedish farming communities. The way in which information on management options moves through a landscape must be an important process in understanding intensification. Thornton and Jones (1998) recently presented a, so far, purely conceptual model of agricultural land-use dynamics, based on Markov chains governed by a few simple decision rules. They state that the construction of this top–down model will be used in further development to interpret possible ecological consequences of changes in input conditions on the landscape. This could lead to the derivation of some simple indices or measures of potential ecological impact of technological and economic change on agricultural land-use, which could be of value in a range of impact assessment studies (Thornton and Jones, 1998, p. 519).

3.3. Optimisation models

In economics, many models of land-use change apply optimisation techniques based either on whole-farm analyses using linear programming, at the microeconomic level, or general equilibrium models, at the macroeconomic scale (Kaimowitz and Angelsen, 1998). Many of these approaches originate from the land rent theory of von Thünen and that of Ricardo. Any parcel of land, given its attributes and its location, is modelled as being used in the way that earns the highest rent. Such models allow investigation of the influence of various policy measures on land allocation choices. However, models of urban and periurban land allocation appear to be much more developed than their rural counterparts (Riebsame et al., 1994). The agricultural land rent theory of von Thünen (1966) does not primarily concern the dynamic process of intensification. It rather explains optimal crop production allocation following degrees of agricultural intensity. In this theory, agricultural systems are found to be centred around a single, “isolated” market place in the form of land-use intensity rings.
However, the central-peripheral concept of decreases in land-use intensity due to land rent differences has been and still is pervasive in modelling. A limited number of variables used in the basic, mainly static and deterministic model of agricultural systems explains intensity as depending on the achievable economic rent. This rent is determined by market demands in the consumer centre, transportation costs, production costs and degrees of perishability of goods produced for the central market. By adopting the model to the case of rotational agriculture, e.g., rotational time (fallow length) was shown to be inversely linked to system parameters as given above. Price expectations and interest rates have also been shown to be important factors. Thus, the results are consistent with the Boserupian contention about a link between population density and degree of agricultural intensity while extending the argument to the effects of the market economy on agricultural intensity (Jones and O’Neill, 1993, 1994). However, the von Thünen model is only partly suitable for prediction in a revised form, e.g., including more variables such as the actual transportation network (Alonso, 1964) and under certain conditions. Such conditions are that demand for products exceeds supply, that transport costs are crucial part of overall costs, and that the model is applied in urban hinterland and isolated commercial market/settlement areas of today’s developing world or in pre-industrial societies of today’s developed world (Peet, 1969). These restrictions are mainly due to market changes and transportation infrastructure which, due to their highly political economy nature, are difficult to predict in the long-term and thus limit predictive power (Guyer and Lambin, 1993).

Optimisation models suffer from other limitations, such as the somewhat arbitrary definition of objective functions and non-optimal behaviour of people, e.g., due to differences in values, attitudes and cultures. While, at an aggregated level, these limitations are likely to be non-significant, they are more important as one looks at fine scale land-use change processes and is interested in the diversity between actors.

3.4. Dynamic (process-based) simulation models

Patterns of land-cover changes in time and space are produced by the interaction of biophysical and socio-economic processes. Dynamic (process-based) simulation models have been developed to imitate the run of these processes and follow their evolution. Simulation models emphasise the interactions among all components forming a system. They condense and aggregate complex ecosystems into a small number of differential equations in a stylised manner. Simulation models are therefore based on an a priori understanding of the forces driving changes in a system. In the case of agricultural intensification, this understanding is rooted in the models of Boserup (1965, 1975, 1981) and Chayanov (1966). These models were powerful stimuli to researchers dealing with agricultural change beyond the confines of economics. The largely population-driven approaches of a Boserupian or Chayanovian type of economy relate agricultural intensification to household needs and wants (amplifying into a consumption-based “needs theory”) according to which households balance consumption and leisure (least-effort means) and/or follow a subsistence target or strategy (“full belly” approach).

Boserup’s intensification model touches the long-run processes of intensification of cultivation as driven by population growth and farmers’ assumed preferences for leisure. It measures increases in frequency of cultivation against constant land and time period and defines a “continuum of agricultural intensity”. The model is mainly applicable in subsistence economies and is valid for the broader sweep of agrarian change history rather than for individual, local cases. The model is based on a rather mechanistic view and is, therefore, hardly suitable for prediction (Lambin, 1994, p. 66, 71). It constitutes a largely verbal and not spatially explicit model that was not designed for numerical prediction — despite attempts to formalise it mathematically at a macro-scale level (Turner et al., 1977). In Chayanov’s “theory of peasant economy”, it is argued that (Russian) farm households did not seek to produce as much as was possible (in profit maximisation), but sought a more restrained and less elastic goal to provision the household. In other words, models of the Chayanovian type refer to situations where agricultural households maximise utility with a trade-off between consumption and leisure, and where farming units are seen not to be integrated into “perfect” markets, i.e., no off-farm labour is assumed.

Different from population approaches that assume subsistence behaviour and limited market integration,
more realistic theorising on longer-term agricultural intensification integrates demands from the market. In a numerical simulation model, Angelsen (1999, pp. 197–201, 204–206) considers land-use intensity as one of 12 variables besides exogenously given prices and a newly introduced labour market — in that any amount of labour can be sold or hired with migrational flows in and out of the local economy. Within market-based theorising, the dominant views used to be based on a purely market or commodity approach. This postulates that farmers accept commodity production and respond to market demands within constraints placed upon them by maximising production to the level of maximum reward. The dominant view has now shifted to the theory of “induced innovation”. Here, risk aversion behaviour, in the form of maintenance of some minimum production for subsistence needs, has gained momentum towards hardly achievable full rational economic efficiency in resource allocation. Kates et al. (1993, pp. 9 and 10) summarised that “induced innovation” implies that technological and institutional changes required for developments in agriculture are endogenously derived as a result of changes in resource endowments and demand. Numerous studies (Binswanger and Ruttan, 1978; Hayami and Ruttan, 1985; Pender, 1998) have focused since then on agricultural innovation and technological change. These factors were considered collectively, e.g., by Goldman (1993), Tiffen and Mortimore (1994), and Tiffen et al. (1994). From these studies, agricultural change emerges as an extremely complex process in the course of which opportunities are as significant as constraints, and the sources of innovation by farmers are multiple (Goldman, 1993, p. 68). While the above studies did not result in dynamic simulation models per se, they allow for a more realistic representation of processes of agricultural intensification in broader simulation models of land-use change (e.g., Stephenne and Lambin, 2001).

The scale issue is difficult to deal with in dynamic simulation models. Process-based models can be parametrised based on local observations of decision-making. These relations can, however, not be used in a straightforward way to model aggregate behaviour. At the landscape level, behaviour is more complex given the numerous interactions between actors and with the biophysical environment (Ahn et al., 1998).

3.5. Integrated modelling approaches

Whilst the previous discussion provides a tidy classification of the various types of models that have been used in land-use change research, newer approaches are increasingly based on combining elements of these different modelling techniques. In principal, the best elements are combined in ways that are most appropriate in answering specific questions. These types of models are increasingly referred to as integrated models, although in many cases they are better described as hybrid models because the level of integration is not always high. Wassenaar et al. (1999), e.g., demonstrated how a dynamic, process-based crop model could be applied at the regional scale through the derivation of statistical relationships between the modelled crop productivity outputs and easily mapped soil parameters. New statistical relationships are derived each time the dynamic model is run, so avoiding the problem of the limited applicability (or transferability) of statistical functions. Such approaches are especially useful where the types of spatially-variable data required by a dynamic model are lacking at the regional scale, but which may be available at well documented sites. White et al. (1997) demonstrated the use of a land-use change model that combined a stochastic, cellular automata approach with dynamic systems models of regional economics. The approach allows spatially-explicit geographic processes to be constrained by less spatially-precise economic processes within the framework of a Geographic Information System (GIS). The approach has been used as a decision support system, by allowing regional land-use planners to investigate the consequences of alternative management strategies.

The combination of dynamic, process-based models with optimisation techniques underpinned the development of the Integrated Model to Predict European Land Use (IMPEL; Rounsevell et al., 1998). The requirement for IMPEL was to be able to assess modifications to the spatial distribution of agricultural land-use in response to climate change. This required a decision-maker (optimisation) orientated approach that was also able to deal explicitly with the impact of climate change on the biophysical components of farming systems (e.g., crop productivity) through the use of dynamic simulation. Whilst, the use of such integrated modelling approaches seem to provide
useful insights into complex land-use systems, one needs to be aware that such models are no longer within the domain of individual researchers, but are increasingly developed within the framework of large, multidisciplinary research teams. This trend away from the simple approaches proposed in earlier models towards increasing size and complexity is perhaps best exemplified by a group of models commonly termed Integrated Assessment Models, e.g., IMAGE (Alcamo et al., 1998). Usually operating at global scales, although still relatively finely resolved in geographic space, models such as IMAGE seek to integrate a wide range of sectors and process descriptions. Integrated Assessment Models are, thus, often well placed to enhance understanding of the consequences of intensification, although seldom able to model the management and decision-making processes of individuals. This stems from their requirement to operate at global scales which often results in simplistic treatment of intensification processes. It is important to note, however, that such models were not designed to assess intensification, but are concerned more with broad scale changes in land cover.

In the context of developing countries, increasing efforts, aimed at integrating various model elements (e.g., guided by the major population and market theories) are obvious from even predominantly economic modelling. An increasing awareness of the significance of spatial explicitness (or regional situations, at least) is also emerging. This is obvious, e.g., from some recent modelling of subsistence agriculture at the forest frontier in the developing world. Angelsen (1994) discusses how variables of the population models such as fallow period and labour input can be integrated in the open economy models. As an outcome of comparing the modelling approaches, Angelsen (1994) suggested consideration of input price developments (e.g., price of fertilisers), risk factors and crop choices, but also the recognition of differences between settled (intensive margin) and frontier (extensive margin) agriculture when evaluating the impact of technological change (Walker, 1999).

4. Case study evidence

The Land-Use/Land-Cover Change (LUCC) programme (Turner et al., 1993), identified the importance of using case study evidence to supplement modelling activities. This leads us to ask, what can be derived from case study evidence to improve our ability to predict land-use intensity? For example, what variables should be included in more “realistic” modelling? The outcomes of two empirical case studies aimed at testing theories and reflecting recent efforts to merge subsistence and market demands (“induced intensification”) are presented below.

In a time series analysis between 1950 and 1986 of the induced intensification theory for 265 households and five villages representing a range of agroecological and socio-economic conditions in Bangladesh, Turner and Ali (1996) stated that the model provided relatively high levels of explained variance in cropping intensity. However, the model also indicated the relative impacts of other important variables such as household class, cropping strategies, environmental constraints (location and water control) and other impediments such as impoverishment, inadequate transportation infrastructure for marketing and unfavourable state policies (e.g., no government assistance in regulating access to water pumps). Though, during the study period, all of the small-holder farmsteads actually produced a small surplus along the lines of induced intensification, the results were achieved under conditions of increasing social polarisation in the course of time, with larger holders accounting for surplus production and increasing landless households suffering from production shortfalls and malnutrition. Thus, adding to a broader social or political economy understanding of land-use intensity changes, the authors also point to the existence of Malthusian-like “thresholds” of intensification that constitute critical junctures in the process and create a series of steps or staircase-like intensification process. Thresholds may serve as major impediments to intensification and either lead to conditions of involution — in the sense of production increases under significant declines in the marginal utility of inputs (Geertz, 1963) — or stagnation, i.e., no or declining production. Thus, notwithstanding environmental and socio-economic constraints to intensification, agricultural growth in Bangladesh was achieved by means of increasing land productivity in the form of intensification through increased irrigation (facilitating double and triple cropping) and the use of green revolution inputs with some thresholds suggesting responses of
involution and stagnation. The latter were adverted first in the 1960s by the adoption of high yielding rice varieties, in the 1980s by a shift to garden crops with high market value, and later with the removal of economic and policy barriers to irrigation technologies. Noteworthy are both the socio-economic impediments or “distortions” (Schultz, 1978) in the form of state regulations or institutional structures and similarly operating environmental constraints (Meertens et al., 1996) to the “ideal” trajectory of induced intensification. Though the diversity of constraints will be difficult to generalise, the point is made that such structures can be so significant as to mask the underlying processes (Turner and Ali, 1996, p. 14986). It is concluded that it is not the process as a whole that is less developed in conceptual terms, but more the specifics that divert intensification into the involution and stagnation paths.

In an evaluation of survey results from 67 small farms in the Kiriyaga District of Kenya between 1981 and 1995, Dorsey (1999) provides findings that expand upon induced innovation and intensification theory supporting the thesis that — despite claimed negative food production trends in Africa — farmers are practising highly productive agricultural strategies resulting from both subsistence and commodity-based production. This rests on the more general observation found in Nigeria by Netting (1993, p. 32) that the main strategy for combining high production per unit area with risk reduction and sustainability is diversification. The Kenyan case study takes the scale of agricultural production (i.e., number of hectares under cultivation per farm) to arrive at a better understanding, and perhaps prediction of intensification and innovation under the constraints of declining land availability. Indicators of agricultural intensification have been identified as a decrease in grazing land (coupled with the effects of a government “zero grazing” programme), rising percentage of available land under production, competition for and fragmentation of land (as measured by a decrease in farm size against rising population density), and widespread capital availability constraints on further production increases. Especially, the latter is considered to be a crucial indicator. The author states that if the scale at which inputs and credit availability become constraints can be specified, a more precise conception of induced intensification may be obtained (Dorsey, 1999, p. 181). Strongly correlated are commercial specialisation and diversification. They both have a strong effect on net income per unit area (reflecting intensification), while the latter is largely seen as a function of how much food production goes toward consumption versus sales (Dorsey, 1999, p. 193). Variations in the interconnectedness of the latter may be explained by constraints and behaviour. Some farmers are risk averse whilst others engage in more risk-taking behaviour. Two other conclusions seem noteworthy. First, no significant relationship has been found between farm size and intensification and, secondly, it is stated that the market demand path may have a greater influence on increased production than population pressure, given that decreases in holding size do not generally lead to declining income per unit area (Dorsey, 1999, p. 192). For other compilations and reviews of studies supporting induced intensification, see Brush and Turner, 1987, and Kates et al., 1993.

5. What is required to be able to predict land-use intensity?

Any model prediction can only be based on what is currently known about processes of change. Case study evidence, however, can highlight the uncertainties and surprises inherent in the processes of land-use intensification. This can both inform model development and reveal a wider range of possible futures than is evident from modelling alone. Moreover, an inductive approach to the understanding of change processes uses a much larger number of variables than are typically represented in a model. The understanding of this complexity helps in turn in deciding what reductions can be performed in model development whilst maintaining the validity of the model. Finally, case studies highlight the importance of decision-making by land managers when facing a range of response options. External driving forces of land-use change open new and/or close old options, but final land management decisions are made by actors who are influenced by socio-cultural and political factors as well as by economic calculations.

Can the question raised in the title be answered? Inevitably, perhaps, the answer is “partly”, although there are clear differences in the capability of
different modelling approaches to assess changing levels of intensification. The answer to the question also depends strongly on the geographic location or socio-economic context of a particular study. It seems that different modelling approaches are more or less appropriate in tackling the question of intensification at different locations. One could anticipate, e.g., using different modelling tools (or a different mix of these tools) when working in developing rather than developed countries. In general, however, dynamic simulation models are better suited to predict changes in land-use intensity than empirical, stochastic or static optimisation models, although some stochastic and optimisation methods may be useful in describing the decision-making processes that drive land management. Moreover, it appears that an integrated approach to modelling (that is multidisciplinary and possibly cross-sectoral) will probably best serve the objective of improving understanding of land-use change processes including intensification. This is because intensification is a function of the management of physical resources, within the context of the prevailing social and economic drivers. Because intensification is driven by management options, the ability to predict changes in land-use intensity requires models of the process of decision-making by land managers. Thus, the ability to model decision-making processes is probably more important in land-use intensification studies than the broad category of model used. For this reason, most landscape change models operating at an aggregated level have not been used to predict intensification. However, there may be opportunities to develop landscape scale models further that explicitly take account of decision-making processes. Actually, issues of intensification are also very interesting — and often more policy relevant — at aggregate scales.

A trend toward integrated models is already evident, although the logistical difficulties in developing such large and complex modelling approaches needs to be recognised. In part, therefore, the future development of such models may depend as much on the willingness of the organisations that fund research as the researchers themselves because large modelling exercises are expensive. Whilst many integrated models draw heavily on existing approaches, there may also be the need to develop new modelling techniques that address intensification issues, specifically. The development of new techniques, however, should be undertaken firmly within the context of the purpose of land-use change models, which is to better understand land-use change processes. Finally, the development of models of land-use intensification has important data requirements as one needs spatially-explicit variables on land management, input use, cropping system, frequency of cultivation, rotations, etc.

Within this context of current model development, there are some simple initiatives that would enhance the ability of the land-use change modelling community to improve its understanding and representation of intensification processes. This includes the development of models that explicitly incorporate management and intensification processes. This will need to consider the spatial scale and its influence on the modelling approach, temporal issues such as dynamic versus equilibrium models, thresholds and surprises associated with rapid changes, and system feedbacks (e.g., the interaction between changes in land management and the quality of soil and biological resources). These models should lead to the formulation of scenarios which would provide plausible representations of alternative futures where these are unknown, uncertain or may contain ‘surprises’. Uncertainties and unknowns might include (bio)technological change, social change, or the role of regulation, policy-making and political change. Scenarios would provide an opportunity to analyse the sensitivities of land-use and management systems as well as allowing us to explore different (sustainable) development strategies and options. Within this context there is a clear need to develop “integrated” scenarios that recognise, in an internally consistent way, that the future will be shaped by socio-economic as well as biophysical change drivers.

6. Conclusion

The type of model needed to predict changes in land-use intensity depends on the specific research question. So far, the emphasis of spatially-explicit landscape models has been on the location issue — where will land-use change take place? With these models, land-use intensification could be treated equally as land-cover conversion. Therefore, for this question, land-use intensification does not require a fundamentally different modelling approach. However, we believe that the most relevant questions
concerning intensification, e.g. for scientific understanding, to predict environmental impacts and to support policies, are related to the quantities of land-use change rather than to the location issue. By quantity, we mean the amount of change that is taking place, i.e. in the case of land-cover conversion, the amount of area changed or, in the case of land-use intensification, the amount of inputs used and/or production per unit area gained or lost, as a function of management level. Model requirements to generate scenarios on the quantity of land-use intensification are more complex compared to models of land-cover conversion. In industrialised regions, predicting land-use intensification requires a better handling of the links between the agriculture and forestry sectors to the energy sector, of technological innovation, and of the impact of agri-environment policies. For developing countries, better representation of urbanisation and its various impacts on land-use changes at rural-urban interfaces, of transport infrastructure and market change will be required. Given the difficulty of specifying future predictions of these driving forces, most of the modelling work will be aimed at scenario analysis. These scenarios should contribute to a better understanding of thresholds involving changes in land-use intensity.

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