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Land in Sight?

Achievements, Deficits and Potentials of Continental to Global Scale Land-Use Modeling

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Abstract

Land use plays a vital role in the earth system: it links human decision making to the terrestrial environment and is both driver and target of global environmental changes. However, decisions about *how much* land to use *where* and *for what* purpose (and the related *consequences*) are still poorly understood. This deficit is in contrast to the fundamental need for global analysis of future land-use change to answer pressing questions concerning e.g. future food security, biodiversity and climate mitigation and adaptation.

In this review we identify major achievements, deficits and potentials of existing continental to global scale land-use modeling approaches by contrasting current knowledge on land-use change processes and its implementation in models. To compare the 18 selected modeling approaches and their applications, we use the integration of geographic and economic modeling approaches as a guiding principle. Geographic models focus on the development of spatial patterns of land-use types by analyzing land suitability and spatial interaction. Beyond,

they add information about fundamental constraints on the supply side. Economic models focus on drivers of land-use change on the demand side, starting out from certain preferences, motivations, market and population structures and aim to explain changes in land-intensive sectors. Integrated models seek to combine the strengths of both approaches in order to make up for their intrinsic deficits and to assess the feedbacks between terrestrial environment and the global economy. Important aspects in continental to global modeling of land use are being addressed by the reviewed models, but up to now for some of these issues no satisfying solutions have been found: this applies e.g. to soil degradation, the availability of freshwater resources and the interactions between land scarcity and intensification of land use. For a new generation of large-scale land-use models, a transparent structure would be desirable which clearly employs the advantages of both geographic and economic modeling concepts within one consistent framework to include feedbacks and avoid redundancies.

1 Introduction

Land use[1] is a crucial link between human activities and the natural environment. Large parts of the terrestrial land surface are used for agriculture, forestry, settlements and infrastructure. This has vast effects on the natural environment. Land use is the most important factor influencing biodiversity at the global scale (Sala et al., 2000). Global biogeochemical cycles (McGuire et al., 2001), freshwater availability (Rosegrant et al., 2002b) and climate (Brovkin et al., 1999) are influenced by land use. Closing the feedback loop, land use itself is strongly determined by environmental conditions. Climate (Mendelsohn and Dinar, 1999) and soil quality affect land-use decisions. For example, they strongly influence the suitability of land for specific crops and thus affect agricultural and biomass production (Wolf et al., 2003).

Given the importance of land use, it is essential to understand how land-use patterns evolve and why. Land-use models are needed to analyze the complex structure of linkages and

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[1] We define land use as the "total of arrangement, activities and inputs that people undertake in a certain land cover type" while "land cover is the observed physical and biological cover of the earth's land, as vegetation or man-made features" (FAO and UNEP, 1999).

feedbacks and to determine the relevance of drivers. They are used to project how much land is used where and for what purpose under different boundary conditions, supporting the analysis of drivers and processes as well as land-use and policy decisions. Based on this, we define *land-use model* as a tool to compute the change of area allocated to at least one specific land-use type.

The importance of land-use models is reflected in the increasing emergence of different modeling approaches and applications. Existing reviews try to structure this abundance by focusing on specific types of land-use changes (e.g. intensification, deforestation), specific modeling concepts (e.g. trade models) or by the development of classification systems. Irwin and Geoghegan (2001) classify models according to their degree of spatial explicitness and economic rationale. In a similar, but more elaborated approach, Briassoulis (2000) applies the criterion of *modeling tradition* in order to distinguish *statistical/econometric, spatial interaction, optimization* and *integrated models* (defining *integration* in terms of consideration of "the interactions, relationships, and linkages between two or more components of a spatial system"). This resembles the approach of Lambin et al. (2000) (and also Veldkamp and Lambin (2001)) who evaluate models concerning to their ability to reproduce and predict intensification processes. They classify models as *stochastic*, *empirical-statistical*, *optimization, dynamic/process-based* and, again, *integrated* approaches where *integrated* refers to a combination of the other categories. Agarwal et al. (2002) compare different approaches to deal with scale and complexity of time, space and human decision-making. Verburg et al. (2004) apply six different criteria, e.g. *cross-scale dynamics, driving forces, spatial interaction,* and *level of integration*, Li et al. (2002) add *cross-sectoral integration, feedbacks, extreme events,* and *autonomous adaptation*. Angelsen and Kaimowitz (1999) provide a meta-analysis of 140 economic-based deforestation models. Van Tongeren et al. (2001), and similarly Balkhausen and Banse (2004) focus on global agricultural trade models.

In this review, we focus on the state-of-the-art in *continental to global* land-use modeling. Global land-use modeling approaches are scarce, although the global scale is important for several reasons: First, many important drivers and consequences of land-use change are of global extent and it is desirable to consider them in a consistent global framework. Secondly, specific processes interlink locations and regions all over the globe: e.g., international trade shifts land requirements from one world region to another, adjacent regions compete for water resources. Furthermore, land-use changes and environmental impacts are often spatially and temporally disjoint (Krausmann, 2004) and thus have to be addressed on an appropriate scale. We focus on land-use models of continental to global scale because these demand specific methodologies that are different from smaller-scale approaches: on the one hand, strategies have to be developed to cope with data limitations. On the other hand, scaling issues have to be addressed appropriately (Veldkamp et al., 2001): processes that are important at smaller scales such as individual decisions by local land users cannot be modeled explicitly on large scales, but their outcome has to be somehow reflected. Abstracting local land-use decision-making to explain regional or global processes has to be seen as a major challenge for large-scale land-use modeling. Potential problems in this context are e.g. discussed by Lambin and Geist (2003) and Geist and Lambin (2004).

Our objective is to provide an overview of land-use modeling *approaches* at the continental to global scale and to identify major achievements, deficits and potentials of existing land-use models at this scale. We do this by **contrasting current knowledge on land-use change processes** (section 2) **and the implementation of this knowledge in current models** (section 3). In order to reflect the *current knowledge*, we first summarize the most important processes of global land-use change and their drivers and consequences as well as the related feedbacks (section 2). In order to reflect the *implementation of drivers, consequences and feedbacks into current models*, we review existing land-use modeling approaches in section 3. We restrict our scope to modeling approaches that are implemented as computer models, excluding purely mathematical models as well as spreadsheet and accounting approaches. In section 4, we discuss to what extend the implementation of current knowledge is limited by data availability. Based on the insights of section 2 (*What is known about land-use change?*), section 3 (*How is this knowledge implemented in global models?*) and section 4 (*To what extend is that implementation facilitated or hampered by data availability?*), section 5 identifies the major achievements, deficits and potentials in global land-use modeling, section 6 concludes.

For the review of modeling approaches, we take the *integration of geographic and economic approaches as a guiding principle*. In our understanding, *geographic models* allocate exogenous area or commodity demand on "suitable locations", where suitability is based on local characteristics and spatial interaction. In contrast, *economic land-use models* base the allocation of land on supply and demand of land-intensive commodities, which are both computed endogenously. With *integrated* we refer to the combination of i) economic analysis of world markets and policies in order to quantify demand and supply of land-intensive commodities and ii) the actual allocation of land use to locations based on geographic analysis. Note that we use the term "integrated" in a more narrow sense than e.g. IPCC (2001) or Parson and Fisher-Vanden (1997) in defining *Integrated Assessment* and also different from Briassoulis (2000) and Lambin et al. (2000), see above.

2 Processes, drivers and consequences of land-use change

Processes, drivers and consequences of land-use change are intimately linked with each other in many ways (Briassoulis, 2000). Here, we provide a short overview only to facilitate the evaluation of modeling approaches. More detailed reviews can be found in Meyer and Turner II (1994) and Dolman et al. (2003). Globally significant land-use change processes include changes in forest cover – mainly in terms of deforestation (Houghton, 1999; FAO, 2003) – and changes in agricultural areas and management (Geist and Lambin, 2002). Changes in urban areas are of minor importance with respect to spatial extent (Grübler, 1994), although they influence global land-use change through rural-urban linkage (Clark, 1998; Delgado, 2003).

Land-use change is driven[2] by a variety of factors, both environmental and societal, which are also scale-dependant, since changes in the spatial arrangement of land use might be undetected if the resolution of analysis is too coarse or if the extent is too small. Thus, our focus on the continental to global scale has direct implications for the selection of drivers.

Concerning the natural environment, **climate** (Ogallo et al., 2000), **freshwater availability** (FAO, 1997; Rosegrant et al., 2002b) and **soil** affect land suitability and thus land-use patterns and are impacted by land-use decisions at the same time (Duxbury et al., 1993; Saiko and Zonn, 2000; van der Veen and Otter, 2001; House et al., 2002; Zaitchik et al., 2002; Lal, 2003).

Various characteristics of societies such as their **cultural background** (Rockwell, 1994), **wealth** (income) and **lifestyle** shape the demand for land-intensive commodities (Delgado, 2003). They are also modulated by land use as resources may be limited and typical commodities may be substituted by others. In this respect, the global context is especially important, as local and regional demands can be met in spatially disjoint regions by international trade (Dore et al., 1997; Lofdahl, 1998).

Besides shaping demand, the societal setting also determines land **management** (Campbell et al., 2000; Müller, 2004) and **political decisions** (e.g. policy intervention in developed countries and development projects in frontier regions of developing countries (Pfaff, 1999; Batistella, 2001)). Other factors include for instance land tenure regimes, the access to markets, governance and law enforcement. Such factors are known to play a decisive role in local and regional land-use change studies (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2001; Geist and Lambin, 2004). However, their impact on large-scale land-use change is unexplored so far.

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[2] A driver of land-use change causes – in our definition – either a change in the total area allocated to a specific land-use type or a change in spatial distribution of land-use types.

3 Land-use models

In the following, we will discuss not only different models but also *different versions or applications* of the *same model* (as for e.g. the IMAGE model, the CLUE model and different versions of GTAP). We did this to catch the different methodological insights to the issue of continental to global land-use modeling, e.g. by coupling the models to other models instead of using them as a stand-alone model. On the other hand, we deliberately excluded some global- to continental-scale models[3] from this review, because they do not provide additional methodological insights compared to models already considered in the review.

Our review of land-use models and their applications (table 1) is structured in three parts. We start with representatives of *geographic models*. Second, macro scale *economic models* and their relation to land issues are discussed. And third, we provide an inventory of *integrated models* (see section 1 for a definition of *integrated*). Note that the structures to present geographic and economic approaches differ fundamentally (see Supplementary table S1): for existing economic models on the global scale, land is not in the focus of interest, but was introduced mainly in order to facilitate an assessment of environmental problems such as climate change. Thus, we discuss the models along general economic modeling concepts and strategies to introduce land and land-use dynamics. In contrast, the reviewed geographic models focus on the process of land-use change itself. Thus, we show the key mechanisms to simulate this process, structured by the common approach of *empirical-statistical* vs. *rule/process-based* (see e.g. Lambin et al. (2000) and Veldkamp and Lambin (2001)): Empirical-statistical models locate land-cover changes by applying multivariate regression techniques to relate historical land-use changes to spatial characteristics and other potential drivers. In contrast, rule/process-based models imitate processes and often address the interaction of components forming a system (Lambin et al., 2000).

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[3] such as e.g. in EPPA (Babiker et al., 2001) and AIM (Matsuoka et al., 1995)

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3.1 Geographic land-use models

Spatially explicit modeling is applied in many disciplines, including both natural and social sciences. However, analyzing the spatial determinants of land use is at the core of geographic science. Geographic land-use studies are mainly concerned with the properties of land, its suitability for different land-use types and its location. Promoted by the introduction of remote sensing and Geographic Information Systems, the application of simulation models boosted, but mostly on local to regional scales (see reviews in section 1). In the following, we will concentrate on geographic models available on large spatial scales.

3.1.1 Empirical-statistical

The CLUE model framework (Veldkamp and Fresco, 1996) was applied and adjusted to several regional case studies, of which two are on the sub-continental scale: for China (Verburg et al., 1999a) and the Neotropics/Tropical Latin America (Wassenaar et al., submitted). The underlying assumption of the CLUE framework is that observed spatial relations between land-use types and potential explanatory factors represent currently active processes and remain valid in the future. The quantitative relationship between observed land-use distribution and spatial variables is derived by means of multiple regression. For this reason, the CLUE model is generally referred to as an *empirical-statistical* model. Nonetheless, statistical analysis is supplemented by a set of transition rules, which additionally control the competition between land-use types. Land-use changes are driven by estimates of national-scale area demands.

The two CLUE applications pursue different objectives and different strategies to deal with scale problems. **CLUE-China** follows a multi-scale allocation procedure. Regression analysis on the coarse resolution (96x96 km^2) is assumed to reveal general relationships between land use and its determining factors over the whole study region, while finer assessments (32x32 km^2) are to capture variability within regions and landscapes (for details see Verburg et al. (1999b)).

CLUE-Neotropics focuses on the identification of deforestation hotspots caused by the expansion of pasture and cropland in the Neotropics. It is assumed that the statistical relationship between grid-based explanatory variables and the actual land-use distribution might differ between different socio-economic and agro-ecological settings. Therefore, separate regression relations are established for defined sub-regions with assumed homogeneous conditions. These sub-regions are derived by intersecting the Farming Systems Map for Latin America and the Caribbean (Dixon et al., 2001) with administrative boundaries. In total, the CLUE approach reflects the complexity of land-use change by applying a broad range of spatial suitability factors. Particularly, it accounts for spatial interaction processes and thus for the dynamic behavior of suitability patterns. This implies the potential of changing suitability patterns to drive land-use changes. Through its multi-scale approach, CLUE is able to reveal scale-dependencies for the drivers of land-use change (Veldkamp et al., 2001). It would thus be desirable to test this methodology for the global scale, too. However, the methodology of regression analysis does not allow for a deeper understanding of the interaction of drivers and processes, which is also acknowledged by the authors. This makes long-term projections difficult, since the empirical relationships cannot necessarily be assumed constant over long time periods. On the other hand, the empirical analysis might help in identifying key processes and thus facilitate the understanding of system behavior.

3.1.2 Rule-based/process-based

The **SALU** model (Stephenne and Lambin, 2001b; Stephenne and Lambin, 2004) is a zero-dimensional model designed to capture the characteristic processes in the Sahel Zone. It has been applied by Stephenne and Lambin (2001a) in order to simulate spatially explicit changes of land use on a very coarse resolution (by dividing the Sahel region into eight independent sub-regions). It provides an appealingly simple approach to endogenously deal with agricultural intensification by focusing on a sequence of agricultural land-use changes not only typical for the Sahelian region: agricultural expansion at the most extensive technological level is followed by agricultural intensification once a land threshold is reached. Exogenous drivers are human and livestock population, rainfall variability and cereal imports. In Sahelian agriculture, intensification mainly takes place as a shortening of the fallow cycle, compensated by additional inputs such as labor and fertilizer, and by the expansion of cropland at the cost of extensive pasture (nomadic grazing). This results in the sedentarization of livestock and overgrazing of remaining pastures (desertification).

This causal chain was recognized as also being relevant in other poorly developed parts of the world (Cassel-Gintz et al., 1997), which inspired the **syndromes concept.** Petschel-Held et al. (1999) define a syndrome of global change as a “non-sustainable pattern of civilization-nature interaction”. Cassel-Gintz and Petschel-Held (2000) applied the syndromes concept to provide global-scale patterns for the occurrence of and susceptibility to deforestation. Deforestation in this context is seen as a consequence of the *Overexploitation Syndrome*, the *Sahel Syndrome* and the *Dust-Bowl Syndrome* (the last two are described in Cassel-Gintz et al. (1997) and Lüdeke et al. (1999)). The syndromes approach does not simulate the area allocated to specific land-use types and thus does not fit into our general definition of land-use models (see section 1). Instead, it provides spatially explicit information about present and future susceptibility towards specific *land-use changes*. For this purpose, it distinguishes between current *intensity* of a syndrome and future *disposition* towards a syndrome. Methodologically, it combines spatially explicit and quantitative data sets with qualitative reasoning by applying the concepts of fuzzy logic. The procedure also accounts for typical tandems and causal chains by considering that a high current intensity of one syndrome (e.g. the Overexploitation Syndrome) together with a high future disposition for another syndrome (e.g. the Sahel Syndrome) might promote deforestation. Thus, the syndromes approach provides information where specific land-use changes might occur. This could basically be integrated into a quantitative framework in order to model actual land-use changes.

3.2 Economic land-use models

Studies of land use and land-use changes have a long history in economic theory. Strictly speaking, (agricultural) land-use studies are the origin of economic science. However, the perception of *land* in mainstream economics has changed tremendously from the only source of "real" production (Physiocrats) to just another primary factor (neoclassical theory, Hubacek and van den Bergh (2002)). Considerations explicitly including land are now treated in specific economic sub-disciplines that are interested in the land-intensive sector such as *Agricultural and Land Economics*, *Environmental and Resource Economics* and, more recently, *New Economic Geography*.

In recent years, the rising interest in science-based assessment and treatment of environmental problems has created a new incentive to reintroduce land into standard economic models as a direct link between economy and environment. In the following, we are introducing models that are examples of the latter tendency. All of them include additional details in their land-use sectors to study the impact of environmental changes on future economic welfare. However, in a strict sense these are not land-use models. Except for the **AgLU** model (Sands and Leimbach, 2003), these models focus on changes in market structure for land-intensive goods or land-use emissions, but not on allocation of land.

3.2.1 Motivation and major characteristics of economic land-use models

Economic science deals with the optimal allocation of scarce resources under the assumption that profit or abstract properties such as welfare are maximized. The same focus applies to the land-use sectors. Market structures are analyzed to understand land-use decisions. This mainly limits the analysis to aspects expressible in monetary terms. Most global economic land-use models are equilibrium models, aiming to explain land allocation by demand-supply structures of the land-intensive sectors. The main mechanism is to equate demand and supply under certain exogenously defined constraints. Besides data tables of in- and output of all included commodities, the most important parameters are elasticities. These describe consumer preferences and the feasibility on the producer's side by determining the impact of input changes on output or input of other commodities. On the broadest level *computable general equilibrium models* and *partial equilibrium models* can be distinguished. In *partial equilibrium models (PEM)* only a subset of the markets is modeled with explicit demand and supply functions, whereas the remaining markets are parameterized (or ignored). An important implication of this approach is the assumption that the markets of interest are negligible for the rest of the economy, since feedbacks with other sectors are largely ignored. In *computable general equilibrium models (CGE)* all markets are modeled explicitly and are assumed to be in equilibrium in every timestep. These models are based on a very rigid theoretical framework, which guarantees market closure. All money-flows are traceable through the whole economy and the structure provides the emergence of feedback effects between sectors (for more detail on CGEs see Ginsburgh and Keyzer (1997) and Hertel (1999)).

Examples of partial equilibrium models are **IMPACT** (Rosegrant et al., 2002a) and **WATSIM** (Kuhn, 2003), modeling only the agricultural sector, the **Global Timber Market Model** (Sohngen et al., 1999) describing the forestry sector, **AgLU** (Sands and Leimbach, 2003; Sands and Edmonds, 2004) and **FASOM** (McCarl, 2004; Adams et al., 2005) which include both the agricultural and forestry sectors. The high resolution of the analyzed sector allows for an in-depth analysis of the respective markets or, due to its simpler market structure, an integration within an integrated modeling framework (as in the case of AgLU).

GTAPEM (Hsin et al., 2004), **GTAPE-L** (Burniaux, 2002; Burniaux and Lee, 2003) and the **G-cubed** model[4] (McKibbin and Wang, 1998) are examples of CGEs. CGEs are often used to analyze the effects of changes in single sectors on the entire economy and vice versa.

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[4] G-cubed really is a mixture of CGE and a macroeconomic model. However, the implication for the agricultural sector is minor.

GTAPEM and GTAPE-L are used to analyze the economic impacts of greenhouse gas emissions and climate change. G-cubed was originally developed to study the impact of global environmental problems on the economy and later extended by inclusion of more detailed agricultural markets in the USA to assess the effects of trade liberalization. For more details on the PEM and CGE land-use models see van Tongeren et al. (2001) and Balkhausen and Banse (2004).

Economic land-use models differ in sectoral and regional resolution (see tables 1 and Supplementary table S1) and in the representation of trade and land. A realistic implementation of international trade is important to properly reproduce food and timber markets. The representation of trade in PEMs is often limited to raw or first-stage processed goods. This excludes processed food products, which account for an increasing share of the world market (van Tongeren et al., 2001). More general, the main issue concerning international trade is whether goods are treated as homogenous or heterogeneous, distinguished by producer and origin. Assuming homogenous goods implies that neither bilateral trade flows nor intra-industrial trade can be represented appropriately. More details on trade can be found in Hertel (1999) and van Tongeren et al. (2001).

In the next section, however, we concentrate on the supply side of land-intensive goods and the treatment of land in the different models since the focus of this paper lies on land allocation.

3.2.2 Land in economic models

In economic models, land is usually allocated according to its relative economic return under different uses. In CGEs, this is commonly achieved via a competitive market of land-intensive products. In G-cubed and GTAPEM land is only used for agricultural production, whereas in GTAPE-L land is also used for forestry and a so-called "others" sector, interpreted as urban land. In PEMs, area is a direct function of own and cross prices and exogenous trends (as in IMPACT and WATSIM), or the result of an optimization of welfare and/or profit (as in the

Global Timber Market Model and FASOM). In AgLU, the share of land for a certain use is proportional to its expected relative profit.

Management practices can be simulated by defining the production of land-intensive commodities as a function of primary factors such as land and labor, and intermediate inputs such as fertilizer and machinery. In order to lower parameter requirements, in CGEs intermediate inputs are commonly modeled as not substitutable to primary factors. This means e.g. that a decrease in land cannot be outbalanced by additional use of fertilizer, implying that intensification and disintensification cannot be represented endogenously (Hertel, 1999). Of the introduced CGEs, only GTAPEM explicitly models the substitution between intermediates and primary factors. Of the introduced PEMs, the Global Timber Market Model and FASOM endogenously simulate management changes. FASOM optimizes over a discrete choice set of alternative management practices, whereas the Global Timber Market Model endogenously determines a management-intensity factor.

An important aspect for the treatment of land in the production process is the heterogeneity of land. The productivity of land can vary across products, management, regions and time. The main reasons for these differences are biophysical characteristics of land, such as climate and soil. A way of introducing heterogeneity into CGEs is to loosen the common assumption that land is perfectly substitutable towards an imperfect substitutability of land between different uses and sectors. In GTAPE-L the standard GTAP model (Hertel, 1997) is modified such that land is modeled as imperfectly substitutable between the different uses. GTAPEM refined this structure by adopting the land allocation structure of the policy evaluation model (OECD, 2003), distinguishing land in the production structure of the agricultural sector even further. The disadvantage of such a non-linear treatment of land in the production functions of CGEs is that land cannot be measured in physical units of area but instead is measured in the value added to the production. This complicates the interpretation of the resulting land allocation.

In partial equilibrium models, land is commonly treated as homogenous. AgLU and FASOM are exceptions. AgLU assumes a non-linear yield distribution decreasing in land. This reflects the assumption that the most productive land is used first, whereas more and more unproductive land has to be utilized for further use, decreasing the average yield per hectare. By introducing a joint yield distribution function, where the yields of different uses are correlated, the conversion possibility from one use to another is characterized. Climate change and technological growth have been introduced by changing the yield distribution (Sands and Edmonds, 2004). FASOM distinguishes four different classes of land mainly based on the slope of land. For timberland, ownership is also a criterion influencing land suitability. Land-allocation changes are only allowed for non-public land. Climate impacts have been studied by introducing externally estimated climate induced yield changes (Alig et al., 2003). The so-called *Agro-Ecological Zones* (AEZ) methodology (Darwin et al., 1995; Fischer et al., 2002) allows an inclusion of environmental changes as e.g. climate change by altering the distribution of land among different classes, which are defined by the dominant climatic and biophysical characteristics. A project is close to its completion, which includes land-use and land cover data in a new version of the GTAP database, allowing for the definition of several AEZ (GTAP, 2005).

GTAPE-L captures another aspect of the land heterogeneity by introducing a so-called *land transition matrix*, tracking all land transformations among the sectors. This distinguishes land according to its history, which is quite unique in economic models. So far, however, the used transition matrix has entries solely for Europe and the USA for only two transformation processes each.

A further aspect of land, not yet touched by any of these models, is the geographic location. To properly introduce geographic location of land, the inclusion of space would be necessary. However, the required existence of an unique equilibrium in macro-economic equilibrium models prohibits the inclusion of increasing returns to scale. Without increasing returns to scale, the scale of production is not defined and thus production is distributed equally over space, hampering any notion of location (Jaeger and Tol, 2002). For a more technical discussion on the topic see Greenhut and Norman (1995a), Greenhut and Norman (1995b), Greenhut and Norman (1995c), Fujita et al. (1999), Surico (2002) and Puu (2003).

3.2.3 Dynamics in economic models

Land-use change is a highly dynamic process. Land-use decisions do not only depend on current and past uses (see section 2), but also on future expectations – especially in slow producing sectors such as the forestry sector, where long-term planning is essential. In economics, *comparative static* (equilibriums that are independent of each other), *recursive dynamic* (previous equilibriums may influence subsequent ones) and *fully dynamic* (all equilibriums for all time-steps solved simultaneously) models are commonly distinguished.

The obvious drawback of comparative static models is that they are not capable of describing any kind of time path and forward-looking behavior. This makes these models rather inappropriate e.g. for detailed forestry studies, since this sector is governed by long-term decisions. GTAPEM and GTAPE-L are representatives of this group of models.

In recursive dynamic models, forward-looking behavior can be implemented by assuming rational expectations based on past experience, as in WATSIM, where the economic agents expect that prices will not change. More often, however, time-dependent variables are updated exogenously. In IMPACT for example, income growth and population, as well as area- and yield growth trends are updated according to exogenous assessments.

In fully dynamic models the time path of variables is based on the assumption of an intertemporarily optimizing agent with perfect foresight. Like this, not only immediate welfare is optimized (as in recursive dynamic models) but also optimal welfare, defined over the whole period, is guaranteed. Apart from the tedious implementation and calibration of such models, their greatest deficit in respect to integrated modeling is the bi-directional notion of time, which hampers online coupling with other models. G-cubed, FASOM and the Global Timber Market Model are fully dynamic models with perfect foresight.

To appropriately model the forestry sector, the inclusion of future expectations is required, which excludes most of the CGEs. But even among the PEMs, agricultural models are more common than forestry models and very few model both sectors. AgLu and FASOM are such exceptions including both sectors in a dynamic fashion and modeling the market competition between them. FASOM simulates the competition for the land among the sectors via a perfectly competitive market. In AgLU land is distributed among forestry and agriculture proportionally to the respective expected economic return. Forward-looking behavior is implemented by equating only one future market at each timestep to determine the expected price for timber in the harvesting year.

3.3 Integrated land-use models

Both economic and geographic land-use models have strengths and weaknesses. Economic equilibrium models can consistently address demand, supply and trade via price mechanisms. They are limited in accounting for supply side constraints, in reflecting the impact of demand on actual land-use change processes and in representing behavior not related to price mechanisms. On the other hand, geographic models are strong in capturing the spatial determination of land use and in quantifying supply side constraints based on land resources. They are more flexible in describing the behavior leading to specific allocation patterns. However, they lack the potential to treat the interplay between supply, demand and trade endogenously. In the following, we will show a selection of models and model applications which try to make up for the deficits of the disciplinary approaches. For all of these models, this is done by coupling *existing* economic optimization models with *existing* tools for spatially explicit evaluation and allocation of land resources (except IMAGE and the IIASA LUC model for China which were rather developed from scratch). The discussed integrated models have different foci: while the **IMAGE** model, the coupled **IFPSIM/EPIC** system and the **ACCELERATES** framework rather focus on the spatially explicit allocation of land-use, the **FARM** model and the **IIASA LUC China** framework rather use spatially explicit evaluation of land resources in order to account for supply side constrains. The coupled **GTAP-LEI/IMAGE** system tries to reconcile these two foci within one framework.

The **IMAGE** model (Alcamo et al., 1994; Zuidema et al., 1994; RIVM, 2001) is a complex framework of dynamically coupled sub-models, providing an interlinked system of atmosphere, economy, land and ocean. The so-called *Terrestrial Environment System (TES)* deals with land-use and land-cover change. Within TES, the *Agricultural Economy Model* (Strengers, 2001) calculates per capita food demand, using "land-use intensities" as surrogates of food prices. Land-use intensities are the amount of land required to produce a unit of food product. Hill-shaped regional utility functions yield a utility value for a given diet. The maximization of the utility function to an optimal diet is constrained by a *land budget*. This is the area needed to produce food at preference levels, reduced by factors depending on income, average potential production and technology. Trade is introduced by exogenously prescribing self-sufficiency ratios for each of the 13 world regions. For timber demand, available forest area at a timestep is considered as surrogate for timber prices. Per capita timber demand is thus computed as a function of income and forest area. The *Land Cover Model* is based on a rule-based preference ranking of the grid cells and serves to allocate the commodity demands on a 0.5° longitude/latitude grid according to land potential. The assessment of land potential for agriculture takes into account neighborhood to other agricultural cells, potential productivity (based on AEZ methodology, (FAO, 1978)), distance to water bodies and human population density. A *management factor* accounts for discrepancies between potential and actual yield. If demand in a specific timestep cannot be satisfied by suitable land, this information is fed back to the Agricultural Economy Model where the available *land budget* is reduced by a scarcity factor and a new optimal demand vector is calculated (iterative procedure).

In total, the IMAGE model has several unique features. First, it is the only model which considers the feedback between land-use change and climate change in both directions. Second, information about land scarcity from the allocation module is fed back to the economic demand module for agricultural commodities. And finally, the competition between the important land-use/cover types is included (albeit simplified and quite ad hoc).

Another approach is applied by the **land-use choice module** (Tan et al., 2003), which dynamically links the **IFPSIM** global partial equilibrium model (Oga and Yanagishima, 1996) to the **EPIC** model (Williams and Singh, 1995). This approach accounts for the agricultural sector only and has two major characteristics: i) land-use decisions are based on price information provided from IFPSIM ii) supply is not calculated within IFPSIM but results from the land-use and yield distribution of the previous time-step. The land-use choice module is a discrete logit choice model operating on a 0.1° grid: in an utility function it considers profit for a specific crop (derived from crop yields and prices) as well as a set of socio-economic variables (population density, accessibility). Crop yields are simulated by a global version of the EPIC model (Tan and Shibasaki, 2003). It should be noted that this approach has yet to be tested and is not applied so far. However, the implementation of a dynamic feedback between the global market of agricultural commodities and the price based decisions of local farmers would add an important aspect to endogenize market driven land-use decisions.

One objective of the **ACCELERATES** framework is to assess the change in agricultural land use on the European level, as a consequence of climate change and European policies (Rounsevell et al., 2003; ACCELERATES, 2004). For this purpose, the **SFARMOD** farm model (Annetts and Audsley, 2002) determines the optimal crop combinations on spatial sub-units (which are based on soil mapping polygons). It emulates farmers' behavior to maximize their long-term profits within the constraints of their situation, taking account of uncertainty in prices and yields. The constraints (water-, temperature- and nitrogen-limited crop yields, sowing and maturity days and the number of workable days) are provided by the **ROIMPEL** model (Rounsevell, 1999), an agro-climatic, process-based simulation model. Besides these constraints, the optimization procedure is driven by exogenously determined crop prices, the cost structure for management operations and historical variability in prices and yields.

Altogether, this can be seen as a bottom-up procedure where the regional land-use distribution is a result of optimized local decisions (similar to the EPIC/IFPSIM framework). However, the degree of macro-economic integration is very low. The SFARMOD model is designed to better reflect farmers' decision making than a regression model would do, however, it might be too detailed to be adapted to the global scale.

An AEZ based approach to modify crop yields according to biophysical factors is applied by the **FARM** model (Darwin et al., 1995; Darwin et al., 1996). The comparative static CGE is based on GTAP, but includes land as primary input to all producing sectors and water as primary input for crops, livestock and services. Water as well as land is modeled as imperfectly substitutable between the sectors and allocated in a perfect competitive market. 6 different AEZs are distinguished according to the length of growing period, which is considered as an appropriate proxy for crop suitability. The impact of climate change on crop productivity is accounted for via a shift in the water endowments and the alteration of the distribution of land across the AEZs. The FARM model was one of the first economic models to use spatially explicit environmental datasets in order to distinguish different land classes and to include the effects of climate change on land allocation. The inclusion of water and its endogenous allocation is unique among CGEs.

The coupling of GTAP-LEI (a version of the GTAPEM) and the IMAGE model within the **EURURALIS** project (Klijn et al., 2005; van Meijl et al., submitted) aims at an even further integration. In GTAP-LEI, GATPEM has been extended by a more elaborate formulation of demand in the animal feed processing sector and by a land supply curve, representing the increase of land prices when land becomes scarce. In the coupled framework, GTAP-LEI replaces the *Agricultural Economy Model* (Strengers, 2001) of IMAGE. Total crop production, as calculated by GTAP-LEI, is interpreted as demand and allocated on grid level by IMAGE as described above. In GTAP-LEI yield is determined by an exogenous trend and by the impact of endogenous management changes, which are modeled as the substitution of primary and intermediate factors (see section 3.2.2.). The exogenous trend is supplied by

IMAGE, where changes in potential yield are modeled as a result of climate change and assumptions on technological progress. The impact of endogenous management change on yields (as modeled in GTAP-LEI) is fed back to IMAGE and used as the management factor described above. This is so far the only approach which couples a full-blown economic land-use model with a full-blown integrated assessment model. The advantage of coupling these models stands against the risk of producing redundancies and inconsistencies, as there is e.g. a land allocation mechanism in both models. As an additional part of the methodology applied within EURURALIS, the land-use patterns computed by the coupled IMAGE/GTAP-LEI models are disaggregated for Europe to a 1-km² grid using the CLUE model. Since this step is not influencing the integration of economic market analysis and the geographic assessment, we do not provide more detail on this.

The **IIASA LUC model for China** (Fischer and Sun, 2001; Hubacek and Sun, 2001) aims at a similar degree of integration, proposing a combination of an AEZ assessment, an input-output analysis and a CGE. The depth of the integration in this approach is remarkable – but it may also hamper its implementation which is still pending. The resulting CGE would not only exchange exogenous parameters with an environmental model but actually synthesize economic and geographic thinking within its theoretical foundation. Future land-use scenarios have been developed by using an extended input-output (I-O) model and spatially explicit measures of land productivity and land availability. An enhanced AEZ assessment model was utilized to provide these measures. By means of empirical estimation the agro-environmental characterization of a spatially explicit production function can be gained from the produced scenarios. This function as well as the projected I-O tables are proposed as the basis of a not yet developed CGE model.

4 Data availability in large-scale land-use modeling

Data for land-use modeling can be structured in four classes (exemplary data sets, collections and reviews are listed accordingly in the Supplementary tables S2-S5): (a) *Current and* *historical land-use data* is needed to initialize, calibrate and validate models and to analyze the determinants of spatial land-use patterns. It includes land cover characterization as well as management information such as (for agriculture) dominant crops, fertilization or irrigation; (b) *environmental data* is needed to determine environmental suitability for different land-use types mainly as a result of climate, terrain and soil conditions; (c) *socio-economic data* is needed in manifold respects: factors determining suitability for land use (such as infrastructure, access to markets), and as drivers and consequences of land use and land-use change (market structures, population and economic development, governance); (d) *scenario data* for future driving forces. These can be environmental or socio-economic, however, they are not accessible via measurement or census, but heavily rely on assumptions on future development. Scenario methodologies may range from simple ad-hoc assumptions, expert judgment or extrapolations up to sophisticated combinations of qualitative storylines with quantitative modeling (Alcamo et al., in press). As they are not measurable in a strict sense, scenario data will not be discussed in further detail as we do in the following for the first three categories.

4.1 Current and historical land-use data

Land-use data are mostly based on census, either available for entire countries (FAO, 2005) or at various sub-national resolutions. In contrast, land cover data are often derived from remote sensing (e.g. IGBPDiscover, GLC2000). However, geographic modelers are interested in the spatial patterns of *land use*: These can be derived by combining the two data sources above, making use of simple allocation algorithms (Ramankutty and Foley, 1998; Leff et al., 2004). However, major inconsistencies between the two data sources indicate their limited quality. This deficit is substantiated by Young (1999), who fundamentally criticizes existing estimates of cultivated land and land still available for cultivation.

Another problem is the availability of spatially explicit time series of land use and cover, needed to analyze *actual changes*. Lepers et al. (2005) provide only a limited solution to that problem by geo-referencing regional studies of land-use changes, partly based on 20-year time series of AVHRR data. From that, they derive so-called "land-use change hot spots" which indicate regions with significant land use dynamics. Ramankutty and Foley (1999) and Klein Goldewijk (2001) provide historical land-use patterns, but only by applying backward simulation on the basis of coarse historical records.

Finally, the management aspect of land-use is insufficiently reflected by available data. Data on fertilization rates is only provided on the country level which is too coarse for large countries. Data on irrigation (Siebert et al., 2002) have a higher spatial resolution, but only indicates the area equipped for irrigation (no information about irrigation intensity and irrigated crops). Other missing data comprise for example forest management and logging practices, and agricultural management aspects, such as crop-livestock integration, livestock farming with zero-grazing, planting dates, typical crop rotations and multiple cropping. A more integrated view on the different aspects of agricultural land use is provided by the farming systems concept: A farming system is characterized by similar resource bases, enterprise patterns, household livelihoods and constraints of farms within a region. Dixon et al. (2001) compiled a geo-referenced database of farming systems for developing and transition countries.

4.2 Environmental data

Environmental data are usually provided on a regular grid, either derived from remote sensing (as for topography), interpolation of point data (as for climate and soil data) or gridded polygon data (as for soil properties). Although environmental data are associated with large uncertainties, general data availability has to be considered as less limiting than for the other data categories. However, there are still deficits: e.g. there is a strong need for quantitative data about soil degradation going beyond the GLASOD study (Oldeman et al., 1990). Climate data are only available on a monthly basis, forcing users to generate artificial daily values e.g. for crop modeling (Tan and Shibasaki, 2003).

4.3 Socio-economic data

Socio-economic data are rarely available at high resolutions. Mostly, data are provided on the national or – at best – sub-national level. Only population-count data (e.g. LandScan), which is also acquired by the help of remote sensing of city night-lights, is available at high spatial resolutions (1km x 1km). The collection of socio-economic data is more costly, more susceptible to uncertainty and of low comparability due to more intransparent and unstandardized collection methods. In addition, data quality differs between regions. Generally, economic data on prices, trade volumes, production and consumption are easier available than rather qualitative data: there are virtually no large-scale data about land tenure systems (e.g. traditional/communal vs. private), the role of subsistence farming, market access, development policies, governance, or institutional enforcement. Such information would already be useful at low spatial resolutions in order to characterize regional differences in land-use dynamics. However, the fuzziness of the variables hampers quantification and application.

4.4 Data integration

As can be seen from all data categories, a limited volume of raw data in terms of census, remote sensing or station measurements is increasingly processed by modeling techniques in order to derive spatially explicit data for land-use models. Processing techniques include simple allocation schemes using remote sensing or proxy data in order to derive spatial patterns from census data (e.g. Leff et al. (2004) for major crops; Siebert et al. (2002) for irrigation; Wood and Skole (1998) for deforestation). Dobson et al. (2000) apply a set of eight proxies to derive human population density (including e.g. slope, road proximity).

Moreover, more complex models provide input data to land-use models such as the global distribution of potential yields or vegetation, again being based on complex environmental data, including the output of climate models. Against this background, it is a major challenge for land-use modelers to carefully reflect on their input data and their origin in order to avoid artifacts in the analysis of land-use patterns or in calibration of model parameters. Nevertheless, the strategy to merge data from remote sensing with ground census still seems to bear large potentials to boost data availability and quality (Perz and Skole, 2003).

5 Major achievements, deficits and potentials

Choosing and classifying relevant modeling approaches is an ambivalent task. On the one hand our focus on *land allocation models* excluded some approaches towards an integration of economy and environment. E.g. Perez-Garcia et al. (2002) is one of the few integrated approaches, where forestry is in the focus of interest. Land and land allocation, however, is not explicitly modeled (or at least not documented). On the other hand, the differentiation into integrated or economic models was not always straightforward. FASOM, for instance, uses EPIC simulation results to include some environmental impacts for agricultural production; GTAPE-L offers a certain degree of integration by including land history, which is a spatial aspect of land; and AgLU not only accounts for certain biophysical characteristics of land, it also is a tool designed to establish a feedback loop with the integrated **Assessment of greenhouse gas emission reduction strategies** model **ICLIPS** (Toth et al., 2003). We decided, however, that the economic basis or the contribution to the economic aspect in these models outweighs the integration aspect. Finally, our aim was to choose a set of representative approaches characterizing the current state-of-the-art. This excludes some modeling approaches which are very similar to the selected ones – though we do not claim these approaches to be irrelevant or less useful.

Each type of land-use change of major importance at the global scale (see section 2) is covered in at least one of the reviewed models. However, not all models include all major types of land use and are – especially in the case of economic land-use models – rarely designed to primarily model land-use changes and the related processes. At the global scale, the EURURALIS framework still addresses land-use changes most explicitly while most global economic models consider land only as an input to production; Syndromes is not intended to allocate land and IFPSIM/EPIC only considers major crops. On the continental scale all the selected models or model applications have an explicit focus on land-use changes (e.g. CLUE, SALU, ACCELERATES, LUC China, FASOM). Concerning FASOM, CLUE-China and CLUE-Neotropics, the applied methodologies could basically be applied to the global scale, too, while ACCELERATES and SALU are rather tailored for regional application and LUC China is not even fully applied within China.

Concerning the reviewed geographic models land is commonly modeled as a carrier of ecosystem goods such as crops or timber. They focus on the dynamics of spatial patterns of land-use types by analyzing land suitability and spatial interaction. Allocation of land use is based either on empirical-statistical evidence (CLUE) or formulated as decision rules, based on case studies and common sense (Syndromes, SALU). Empirical-statistical approaches can account for a large choice of suitability factors, spatial interaction and thus dynamic suitability patterns. Beyond, they can explicitly account for scaling issues by performing the statistical analysis on different scales and thus revealing scale dependencies of drivers. Rule-based models are based on a certain understanding of land-use decisions. Thus, they are able to reproduce causal chains (e.g. explaining intensification and degradation in the Sahel Zone), the synergetic interaction of drivers and processes or the impact of governance (Syndromes approach). However, upscaling of decision-making processes is not explicitly discussed in the reviewed modeling studies (see below).

In contrast to the geographic approach, economic models focus on drivers of land-use change on the demand side. They represent trade, which shifts land requirements from one world region to another. However, the actual impact of trade on land-use changes is rarely explicitly addressed in the reviewed studies. Land is usually implemented as a constraint in the production of land-intensive commodities and the focus is more on the outcome of land use than on its allocation. The economic competition of different uses within one sector is represented endogenously. The simulation of management changes as well as the competition among different sectors are supported by the structure of such models but seldom actually included. This strongly limits the representation of land-use change processes (see Supplementary table S1). Land is often utilized in one sector only, but even the inclusion in several sectors does not guaranty a proper representation of land-use changes. FASOM and AgLU are the only economic models that provide an appropriate framework to model competition and resulting changes between two land-intensive sectors (agriculture and forestry). But as partial equilibrium models (and FASOM additionally due to its regional focus) their representation of global trade is limited. The inclusion of management changes or technological progress is hampered by the models' internal representation of the production process (see section 3.2.2) and data availability. The inclusion of a production structure allowing for substitution of primary and intermediate goods in GTAPEM, however, is a first step towards a better representation of management changes in CGEs.

Current integrated land-use modeling approaches provide evidence that some of the intrinsic deficits of geographic and economic approaches can be overcome to a certain extent. Several strategies of integration can be identified: Some studies employ a land allocation scheme, which uses demand or price information from economic models to update land-use patterns in detailed environmental models (ACCELERATES, IFPSIM/EPIC). The land-use choice model in the EPIC/IFPSIM approach determines the supply side outside the trade model and thus allows for a dynamic feedback between land-use patterns and global demand. IMAGE computes demand internally without external price information. It is the only model which accounts for the feedback of land scarcity on demand although the economic demand module is theoretically weak, as also admitted by its author (Strengers, 2001).

The coupling of IMAGE and GTAP-LEI in the EURURALIS project aims to improve on this weakness. It enhances the economic foundation of the IMAGE land-use model and improves the representation of land supply in the GTAPEM version. Beyond, a first step towards a representation of the relation between land scarcity and intensification has been achieved by implementing a land supply curve in GTAP-LEI. The remaining integrated approaches focus on improving the representation of the supply side within a general equilibrium approach by considering spatially explicit environmental information: In FARM, different land types are distinguished and evaluated (AEZ methodology) whereas in IIASA LUC China the entire supply function is planned to result from environmental and economic analysis. In addition, these models also refine their land allocation mechanism. FARM for instance, includes land in all sectors, enabling competition for land[5]. Additionally, a competitive market for water is implemented, which improves the representation of management.

Despite these achievements, the full potential of integrating economic and geographic approaches seems not to be fully explored, yet. For the coupling of different modeling approaches as in the EURURALIS framework, the advantages of process detail stands against the risk of inconsistencies and redundancies. The reviewed models lack endogenous approaches to determine whether food demand will be satisfied rather by expansion of agricultural area than by the intensification. Beyond a more detailed representation of agricultural management, including the feedback with soil and water is also needed. Irreversibly degraded soil or the exhaustion of freshwater resources are major constraints on future land use, that have not yet been tackled sufficiently by any land-use model. Admittedly, there are several models which consider irrigation and FARM even includes the competition for water among water-intensive sectors. However, water resources are not bound to environmental processes in these models, so that no feedback loop is established. Yet, it should be critically assessed whether all these issues can be addressed within one single framework or rather in related scenario storylines.

Other methodological challenges are still ahead. The problems associated with different time-scales and dynamics are often ignored. Environmental studies operate on large temporal scales of up to 100 years or even more. Studies including human behavior are designed to operate on smaller time scales, typically ten to twenty years. Predominantly, the parameterization of human reactions and behavior makes long-term projections highly uncertain, as it is mainly based on current or past observations. This also holds true for the

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[5] But the comparative static setting prohibits an inclusion of planning based on foresight for the forestry sector.

economic approach which uses motivation based theory instead of observed behavior. The same applies for spatial scales. How can human behavior be described at a continental to global scale? Individual behavior cannot be simply transferred to the continental or global scale. Empirical geographic models implicitly account for scale effects by using regression techniques on the scale of application. Rule-based models have more problems in generalizing local behavioral patterns to large scales. The Syndromes approach suggests a way to base such up-scaling tasks on large-scale process patterns (called Syndromes). However, large-scale modeling studies rarely explicitly address the scaling issue. There could be some potential in combining empirical-statistical approaches with rule- or process-based settings in order to explore scale dependencies of drivers while employing explicit process description.

Moreover, the interpretation of parameters can differ tremendously among different models. An obvious example is the representation of land in CGEs as value added for the production. A simple mapping from dollars to hectares will not be sufficient to account for the different underlying interpretations.

6 Conclusions

Global land-use modeling approaches are scarce in spite of the importance of the global context for land-use change processes. Current approaches to continental and global land-use modeling bear the potential to model land-use dynamics but still need further efforts since land-use is rarely the primary objective of these models. The strength of economic models is the description and quantification of drivers on the demand side. They provide a structure to represent the competition among different sectors, changes in management and technology and demand shifts due to trade or policy interventions. Geographic models explicitly address information on fundamental constraints on the supply side and allow for path dependence by tracking inventories of land and their productive potential. Beyond, they are flexible and open to integrate socio-economic drivers and their synergies (Geist and Lambin, 2002; Lambin et al., 2003). Integrated models seek to combine these strengths in order to make up for the intrinsic deficits of both approaches and thus to assess the feedbacks between terrestrial environment and global economy.

But despite the achievements and individual strengths of the selected modeling approaches, core problems of global land-use modeling have not yet been resolved. Scaling issues are rarely explicitly discussed. Models need to address several land-use types and their drivers simultaneously in order to account for their competition. Beyond, the inclusion of feedbacks between society and environment are needed and call for further efforts in integrated land-use modeling. For a new generation of integrated large-scale land-use models, a transparent structure would be desirable which clearly employs the discussed advantages of both geographic and economic modeling concepts within one consistent framework and avoids redundancies. For this purpose, suitable access points for model coupling need to be identified.

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Table 1 Land-use models covered in this review: Overview

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
CLUE-China	Verburg et al. (1999a); Verburg et al. (1999b)	1-year steps; 1990 - 2010	*Multi-scale*: (China): 96x96 km grid; 32x32 km grid; subgrid; National level (China)	Observed spatial relations are assumed to represent currently active processes; allocation of area demands based on preference maps (generated through regression analysis)	Assessing the spatial impact of national scale demand trends on the spatial distribution of land-use types	Geographic (empirical-statistical)
CLUE-Neotropics (based on CLUE-S)	Wassenaar et al. (submitted) (based on Verburg et al. (2002))	1-year steps; 1990 - 2010	*Multi-scale:* (Neotropics): national level, farming systems sub-units, 3x3km; Sub-continental (Neotropics)	see CLUE-China; additionally enhanced spectrum of location factors; using spatial sub-units for regression analysis based on Farming Systems Map	Identifying deforestation hotspots due to the expansion of pasture and cropland	Geographic (empirical-statistical)

Model/ Modeling Framework	**Literature**	**Temporal resolution and coverage**	**Spatial resolution and coverage**	**Main mechanism**	**Motivation**	**Classification**
SALU	Stephenne and Lambin (2001a); Stephenne and Lambin (2001b)	1-year steps; 1961-1997	*Multi scale:* (Sahel); country level; 2.5° lat/ 3.75° lon grid; Sub-continental (Sahel zone)	Rule-based representation of the causal chain typical for land-use change in the Sahel zone: Transition from extensive to intensive use triggered by land scarcity thresholds	Reconstructing past land cover changes for Sudano-Sahelian countries as input for GCMs	Geographic (rule-/process-based)
Syndromes	Cassel-Gintz and Petschel-Held (2000)	*no explicit representation of time*	5 min. lon/lat ; Global	Not a land-use model in a strict sense; rather maps present and future susceptibility towards specific land-use changes, in this case deforestation; based on fuzzy-logic	Identifying hotspots with high disposition for current and future deforestation	Geographic (rule-/process-based)

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
AgLU	Sands and Leimbach (2003)	15-year steps; 1990-2095	11 regions; Global	Partial equilibrium; land share proportional to economic return of the land; joint probability distribution function for yield	Simulate land-use changes and corresponding GHG emissions to feed into integrated modeling framework	Economic
FASOM[6]	McCarl (2004); Adams et al. (2005)	5-year steps; 2000-2100	Multi-scale: 11 US regions (broken down into 63 for agriculture) 28 international regions (for trade) National[7] (USA)	Partial equilibrium; non-linear mathematical programming; endogenous modeling of management; Competition of forestry and agricultural sector for land	Studying impacts of policies, technical change, global change on agricultural and forestry sector	Economic
IMPACT[5]	Rosegrant et al. (2002a)	comparative static; 1997-2020	36 regions; Global	Partial equilibrium	Analyze the world food situation	Economic

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[6] For FASOM and IMPACT a great variety of different model versions are around. The stated properties might vary between the different versions.

[7] Global coverage for trade

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
G-cubed (Agriculture)	McKibbin and Wang (1998)	1-year step; 1993-2070	12 regions; Global	General equilibrium + macroeconomic behavior	Exploring the impact of international and domestic stocks like trade liberalization on US agriculture	Economic
GTAPE-L	Burniaux (2002)	comparative static; baseyear 1997	5 regions; Global	General equilibrium + transition matrix, accounting for the history of land	Exemplify the incorporation of land /land use in GTAP; Assessing GHG mitigation policies with focus on land-use impacts	Economic
Global Timber Market Model	Sohngen et al. (1999)	1-year steps; 1990-2140	10 regions; Global	Partial equilibrium; Welfare optimization with perfect foresight	Studying the impact of set-aside policies and future timber demand on forest structure and cover, timber markets and supply	Economic

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
GTAPEM	Hsin et al. (2004)	comparative static; 2001-2020	7 regions; Global	General equilibrium + refined transformation structure for agricultural land + substitution possibility among primary and intermediate inputs	Improve the representation of the agricultural market	Economic
WATSIM	Kuhn (2003)	1-year steps; 2000-2010	9 regions; Global	Partial equilibrium + quasi dynamic price expectations	Study the influence of trade policy on agricultural sector	Economic
IMAGE Land Cover Module	Alcamo et al. (1998)	1-year steps; 1970 - 2100	*Multi-scale*: 13 world regions, 0.5° grid, subgrid; Global	"Agricultural Economy Model" calculates demands for agricultural and forest products; land is allocated on a rule-based preference ranking	Integrated assessment of Global Change	Integrated
IFPSIM-EPIC	Tan and Shibasaki (2003); Tan et al. (2003)	not documented	*Multi-scale*: 32 world regions, 0.1° grid level; Global	Land productivity (based on EPIC) and crop prices (based on IFPSIM) are assumed to be major determinants of agricultural land use decisions	Analyzing the relation between land-use patterns and global agricultural markets	Integrated

Model/ Modeling Framework	**Literature**	**Temporal resolution and coverage**	**Spatial resolution and coverage**	**Main mechanism**	**Motivation**	**Classification**
ACCELERATES	Rounsevell et al. (2003)	2000-2050; comparative static	*Multi-scale:* Countries; soil mapping units, NUTS2; Europe	Calculation of optimal crop combinations on spatial sub-units; assumes generic farmers who maximize their long term profits	Assess the vulnerability of European managed ecosystems to environmental change	Integrated
GTAP-LEI/ IMAGE coupling within EURURALIS	(Klijn et al., 2005); van Meijl et al. (submitted)	10-year steps; 2001-2030	*Multi-scale:* national level, sub-national level (NUTS2), grid level; Global with focus on EU15	Coupling of a variant of GTAPEM (GTAP-LEI) and IMAGE Using management factor and food & feed production to update IMAGE and yield and livestock conversion factor to modify production in GTAP-LEI	Assessing impact of different policies on land use in Europe	Integrated
LUC China	Fischer and Sun (2001); Hubacek and Sun (2001)	so far quasi static; 1992 - 2025	*Multi-scale*: 8 economic regions, 5x5 km grid; National (China)	Combining AEZ assessment, extended I/O-analysis and scenario analysis to develop a spatially explicit production function for a CGE model	Analyzing alternative policy scenarios	Integrated

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
FARM	Darwin et al. (1996)	comparative static; 1990-2090	*Multi-scale*: 8 regions, 0.5° lon/lat ; Global	General equilibrium + land and water as primary inputs (imperfectly substitutable) in all sectors; AEZs defined by spatial explicit environmental data	Integrating explicit land and water assessment into CGE, environmental focus on climate change	Integrated

Supplementary table S1 Selected properties of large-scale land-use models. Double-headed arrows represent bidirectional feedbacks; single-headed arrows represent causal chains that lack a feedback.

Model/ Modeling Framework	**Land use/cover types**	**Land-use change processes**	**Land-using Sectors**	**Land-using Commodities**	**Inter-national trade**	**Feedbacks/ causal chains**
CLUE-China	Cropland, forest, grassland/pasture, horticulture, urban, unused	De-/Reforestation, agricultural expansion/abandonment, urban growth	-	-	-	Spatial interaction enables dynamic preference maps
CLUE-Neotropics	Cropland, forest, grassland/pasture, shrub, unused	See CLUE-China	-	-	-	See CLUE-China
SALU	Cropland, forest, grassland/pasture, unused	Deforestation, agricultural expansion/abandonment, intensification	-	-	-	Land scarcity →intensification →degradation →land scarcity
Syndromes	Forest, other	Deforestation	-	-	-	-

Model/ Modeling Framework	Land use/cover types	Land-use change processes	Land-using Sectors	Land-using Commodities	Inter-national trade	Feedbacks/ causal chains
AgLU	-	De-/Reforestation, agricultural expansion/abandonment	Agriculture (Crops, Commercial Biomass & Livestock), Forestry	3 agricultural (one each), 1 forestry	Unilateral	Land use ↔ commodity prices climate → land use
FASOM	-	De-/Reforestation, agricultural expansion/abandonment, intensification/ extensification	Agriculture (Crops, biofuel & livestock), Forestry	52 agricultural (24 crops, 2 biofuel, 26 livestock), 20 forestry	Unilateral	Climate → land use Land-use/management change ↔ price and cost changes
IMPACT	-	Agricultural expansion/abandonment	Agriculture (crops and livestock)	16 (6 livestock, 10 crops)	Unilateral	Land use ↔ commodity prices
G-cubed (Agriculture)	-	-	Agriculture (crops and livestock)	4 (3 crops, 1 livestock)	Bilateral	Land use ↔ commodity prices
GTAPE-L	-	De-/Reforestation, agricultural expansion/abandonment urban growth[8]	Agriculture (crops and livestock), Forestry, Others	3 agricultural (2 crops, 1 livestock) 1 forestry	Bilateral	Land use ↔ commodity prices

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[8] urban growth in the sense that a shift to industrial land use can be modeled

Model/ Modeling Framework	**Land use/cover types**	**Land-use change processes**	**Land-using Sectors**	**Land-using Commodities**	**Inter-national trade**	**Feedbacks/ causal chains**
Global Timber Market Model	-	Forest-management change	Forestry	1 forestry	No trade modeled	-
GTAPEM	-	Intensification/ Extensification	Agriculture (crops and livestock)	10 (8 crops, 2 livestock)	Bilateral	Land use ↔ commodity prices
WATSIM	-	-	Agriculture (crops and livestock)	18 (12 crops, 6 livestock)	Bilateral	Land use ↔ commodity prices
IMAGE Land Cover Module	Cropland, forest, pasture, urban, 14 biomes incl. forest	De-/Reforestation, agricultural expansion/abandonment, urban growth	Agriculture (crops and livestock), Forestry, Energy	7 food crops, 4 biofuel crops, grass and fodder, 1 forestry	Unilateral (based on self-sufficiency ratios)	Land use ↔ climate, land scarcity ↔ commodity demand
IFPSIM-EPIC	Agriculture	Agricultural expansion/abandonment	Agriculture	Not documented	Unilateral	Land use ↔ commodity prices
ACCELERATES	Agriculture	Agricultural expansion/abandonment	-	12 crops	-	-

Model/ Modeling Framework	Land use/cover types	Land-use change processes	Land-using Sectors	Land-using Commodities	Inter-national trade	Feedbacks/ causal chains
GTAP-LEI/ IMAGE coupling within EURURALIS	Cropland, forest, pasture, urban, 14 biomes incl. forest	De-/Reforestation, agricultural expansion/abandonment, urban growth Intensification	Agriculture (crops and livestock)	10 (8 crops, 2 livestock)	Bilateral in GTAP-LEI, unilateral in IMAGE	Climate ↔ Land use ↔ commodity prices, production specification, land scarcity ↔ yield, commodity demand, land price
LUC China	Cropland, grassland, forest	De-/Reforestation, Agricultural expansion/abandonment, urban growth[1]	Agriculture (crops and livestock) Forestry, others	Not clearly documented	No international trade	Environmental conditions → future scenarios → production function specifications (theoretically → environment)

Model/ Modeling Framework	**Land use/cover types**	**Land-use change processes**	**Land-using Sectors**	**Land-using Commodities**	**Inter-national trade**	**Feedbacks/ causal chains**
FARM	-	De-/Reforestation, Agricultural expansion/abandonment,, urban growth[1]	Agriculture (crops and livestock), Forestry, others	4 Agriculture (3 crops, 1 livestock) 1 Forestry, 8 *others*	Bilateral	Climate → land use

Supplementary table S2 Selected Example reviews and data sets describing global land use and land-use changes

Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
PAGE Agroecosystems	Wood et al. (2000)[9]	Review	Lists data sets describing extent, distribution and change of agroecosystems	Various	Various	Various
PAGE Grassland Ecosystems	White et al. (2000)[10]	Review	Lists data sets describing extent, distribution and change of grassland ecosystems	Various	Various	Various
PAGE Forest Ecosystems	Matthews et al. (2000)[11]	Review	Lists data sets describing extent, distribution and change of forest ecosystems	Various	Various	Various
GLC2000	Joint Research Centre (2003)[12]	Map	Global land cover distribution	Grid	Global; 30 sec. lon/lat	2000
IGBPDiscover	Loveland et al. (2000)[13]	Map	Global land cover distribution	Grid	Global; 30 sec. lon/lat	1992
MODIS	Friedl et al. (2002)[14]	Map	Global land cover distribution	Grid	1x1km	From 2000

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Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
Global Forest Resources Assessment	USGS EROS Data Center (2000)[15]	Map	Describes state and conditions of forest resources for the year 2000 and changes over the last 20 years	Grid	Global; 30 sec. lon/lat	2000
FAOSTAT	FAO (2005)[16]	Database	Comprehensive data collection about land use and cover, management, agricultural markets	-	Global; national level	1961 - 2003; annual
-	Ramankutty and Foley (1998)[17]	Map	Maps worldwide distribution of croplands by combining sub-national census data with remote sensing	Grid	Global; 5 min. lon/lat	1992
-	Ramankutty and Foley (1999)[18]	Map	Maps worldwide historical distribution of croplands	Grid	Global; 30 min. lon/lat	1750 - 1992; variable timestep
-	Leff et al. (2004)[19]	Map	Maps worldwide distribution of 17 field crops by combining sub-national census data with remote sensing	Grid	Global; 5 min. lon/lat	1992
-	IFA (2002)[20]	Spreadsheet	Crop specific fertilizer application rates	-	Global, but incomplete; national level	Mid 1990s

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Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
Map of irrigated areas	Döll and Siebert (2000)[21]; Siebert et al. (2002)[22]	Map	Maps distribution of areas equipped for irrigation	Grid	Global; 5 min. lon/lat	Mid 1990s
Global Farming Systems Map	Dixon et al. (2001)[23]	Map	Applies a methodology to define predominant farming systems dependent on a variety of criteria such as predominant crops, management level, crop-livestock integration, dominant livelihood	Polygon	Developing and transition countries	Mid 19990s
Agro-MAPS	FAO (2003)[24]	Map	Sub-national census data about cultivated crops (area, production)	Polygon	Africa (to be extended globally); size of polygons depends on administrative unit	1981-2002; annual timesteps
HYDE	Klein Goldewijk (2001)[25]	Map	Distribution of historical land cover (rather backward modeling)	Grid	Global; 30 min lon/lat	1700-1990; variable timesteps

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Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
FARM Database	Darwin et al. (1995)[26]	Data Collection	Crop, livestock, and forestry commodity production agricultural water withdrawals for livestock and irrigation; length of growing season and thermal regime; land cover	Geodatabase	Global; national and 30 min. lon/lat	1997
-	Thornton et al. (2002)[27]	Map	Distribution of poverty and livestock in developing countries	Grid	Developing and transition countries; 2.5 min lon/lat	Mid 1990s
Human Footprint Map	Sanderson et al. (2002)[28]	Map	Maps the influence of human by overlay of several proxies fro human influence such as distance to roads and rivers, land cover etc.	Grid	Global, 30 sec. lon/lat	Mid 1990s
Areas of rapid land-use change	(Lepers et al., 2005)[29]	Map	Maps hot spots of rapid land-use change between 1981 and 2000, including change of croplands, deforestation, dryland degradation, tropical wild fires	not documented	Global	1981 - 2000

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Supplementary table S3 Exemplary reviews and data sets describing environmental conditions

Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
Global Agroecological Zones	Fischer et al. (2002)[30]	Map	Modeling results describing the global distribution of suitability for several agricultural land utilization types, based on a variety of global data sets which are listed here as well; additionally a number of climate characteristics such as length of growing period etc.	Grid	Global; 5 min. lon/lat	1961-1990 climate normal period; one time period
CRU Baseline Climate	New et al. (2000)[31]	Map	Climate indicators on monthly basis including precipitation, temperature, number of wet days, cloudiness, radiation etc.	Grid	Global; 30 min. lon/lat	1901 - 1995; climate normals and monthly time series
GTOPO30	United States Geological Survey (1998a)[32]	Map	Digital elevation model from remote sensing	Grid	Global; 1x1 km	-

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Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
HYDRO1K	United States Geological Survey (1998b)[33]	Map	Derivative data based on GTOPO30: aspect, slope, flow directions, flow accumulation, comouind topographical index	Grid	Global; 1x1 km	-
FAO Digital Soil Map of the World	FAO (1995)[34]	Map	Global map of dominant soil types and derivative class data including e.g. pH, texture, organic carbon, nitrogen, effective soil depth	Grid and Polygon	Global; variable polygon sizes; 5min lon/lat	-
ISRIC-SOTER	UNEP et al. (1995)[35]	Data Collection	Comprehensive soil data portal with geo-referenced soil profile data, soil unit maps, derived soil properties, soil degradation (GLASOD, ASSOD, SOVEUR)	Grid, point, polygon	Continental to global; variable resolution	-

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Supplementary table S4 Selected reviews and data sets describing socioeconomic conditions

Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
LandScan 2002	Dobson et al. (2000)[36]; Bhaduri et al. (2002)[37]	Map	Population density derived from several proxies such as night-time lights, infrastructure and others	Grid	Global; 30 sec. lon/lat	2002
FAOSTAT	FAO (2005)[9]	Database	Indicators related to agricultural and timber markets	-	Global; country level	1961 - 2003; annual
VMAP Level 0	NIMA (1998)[38]	Map	Major road and rail networks, hydrologic drainage systems, utility networks (cross-country pipelines and communication lines), major airports, elevation contours, coastlines, international boundaries and populated places	Vector arcs, points	Global; 1:1000,000	-
Human Development Reports	UNDP (2003)[39]	Report and spreadsheet	Among other development indicators: time series of human development index (aggregate figure of live expectancy, education and income)	-	Global; country level	1975 - 2002; five year timesteps

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Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
World Development Reports	World Bank (2005)[40]	Report and spreadsheet	Comprehensive collection of socio-economic variables on country level, including e.g. GDP/GNI, gender issues, governance, infrastructure, poverty, rural development and many others	-	Global; country level	1960 - 2003; annual
ICRG Risk Ratings	PRS-Group (2005)[41]	Spreadsheet	Commercial data portal offering risk indicators such as conflicts, corruption, bureaucracy quality etc.	-	Global; country level	1984 - 2003; annual
GTAP	GTAP (2005)[42]	Model/Database	Global data base describing bilateral trade patterns, production, consumption and intermediate use of commodities and services	-	Global; various, latest version with 87 regions	CGEs for several time slots, starting in the 1990s

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Supplementary table S5 Selected reviews and data sets describing future scenarios of driving forces

Name	**Reference**	**Source type**	**Relevant contents**	**Spatial format**	**Spatial coverage and resolution**	**Temporal coverage and resolution**
World Agriculture Towards 2015/30	(FAO, 2002)[43]	Report	Projection of future areas for specific crops, irrigation and others	-	Global; country level	2015 and 2030
Fertilizer requirements in 2015 and 2030	(FAO, 2000)[44]	Report	Projection of future fertilizer requirements	-	Global; world regions	2015 and 2030
	IPCC (2001)[45]	Data Collection	Collection of climate change scenarios, based on different socio-economic scenarios	Grid	Global; various	1990 - 2100; monthly
Special Report on Emissions Scenarios (SRES)	IPCC (2000)[46]	Report	Socioeconomic-scenarios of population growth, economic development and others, based on modeling outputs	-	Global; 11 regions	-
SEI Scenarios	Raskin et al. (2002)[47]	Report	Socioeconomic-scenarios of population growth, economic development and others, based on modeling outputs	-	Global; 11 regions	1990 - 2050

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