Land **2014**, *3*, 793-833; doi:10.3390/land3030793

OPEN ACCESS

land

ISSN 2073-445X
www.mdpi.com/journal/land/

Review

Climate–Human–Land Interactions: A Review of Major Modelling Approaches

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Received: 5 April 2014; in revised form: 14 May 2014 / Accepted: 8 July 2014 / Published: 22 July 2014

Abstract: International agreements on climate change have highlighted the role of land in climate and human dynamics, making it an issue of global importance. The modelling of land-related processes, sectors, and activities has recently become a central topic in economic and policy theory, as well as within environmental sciences. Modelling strategies have been improved and new datasets have come into light for land-cover and land-use change analysis. However, unexpected human behavior and natural constraints challenge the modelling of interdependences and feedback mechanisms amongst economies, societies, and the environment, resulting from land-use and cover change. This paper provides a detailed overview of the most representative and advanced methods and models developed to represent climate–human–land interactions. It offers a critical discussion about relevant methodological aspects, missing knowledge, and areas for future research.

Keywords: land-use and land-cover change modelling; climate feedbacks; human interaction; model integration; Integrated Assessment Model; Earth System Model

AEZ	Agro-Ecological Zoning
AR5	Fifth Assessment Report
AOGCM	Coupled Atmosphere-Ocean General Circulation model
BLS	Basic Linked System
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium Model

CMIP5	Climate Research Programme's Fifth Coupled Model Intercomparison Project
DGVM	Dynamic Global Vegetation Model
ESM	Earth System Model
EU	European Union
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GCM	General Circulation Model
GIS	Geographic Information System
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LCC	Land-Cover Change
LSM	Land Surface Model
LULUCF	Land-Use, Land-Use Cover, and Forestry
LUC	Land-Use Change
PEM	Partial Equilibrium Model
PFT	Plant Functional Type
ppmv	Parts Per Million by Volume
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
USEPA	U.S. Environmental Protection Agency
WHRC	Wood Hole Research Centre

1. Introduction

Land-use and land-cover change derive from the complex interaction of a big number of factors both natural and human induced [1,2]. The final land-use scenario is a function of the interactive processes of climate change, economic development and demographic expansion, definition of environmental policies, and pricing of land and land-related commodities. In its turn, land-use change influences the land cover through deforestation, afforestation, agriculture, pasture, forest management, and expansion of urban areas. This alters the properties of the land surface-atmosphere interaction which affects global climate, especially in the regions where social activities are potentially exposed to climate extremes [3].

A number of technical and data-related issues has been hindering a complex design of the land system, especially at the global scale. First, the scarce interdisciplinary collaboration of the past has led to the consideration of changes in land distribution across space from either an economic or a geographical/biophysical standpoint, and rarely as the result of a multi-sided issue. Consequently, important connections and feedbacks between and from the economic and physical spheres have been left outside the scope of most analyses. Second, the lack of information for many land-based parameters and for several regions of the world has confined research to geographically restricted areas. Third, the absence of a full understanding of climate processes and the way in which land-use changes affect (and interact with) regional and global climate and biogeochemical cycles have discouraged investigations exploring the joint effects of biogeochemical and biogeophysical impacts of land-use change on climate [3]. Finally, the huge number of uncertainties still permeating models, theories, sciences, and data has further hampered the progress in this field.

However, most recently, international agreements on climate have strengthened the relevance of land use, land-use change, and forestry dynamics (LULUCF). Similarly, the role of land in providing relevant food and energy products and services has further increased the urgency to develop a proper land representation [4]. For example, only lately have LULUCF become central topics in economic theory [5,6]. Similarly, global-scale datasets for land management (planting, harvesting, fertilizers, and irrigation) have been developed behind vegetation mapping to simulate biogeophysical and biogeochemical effects of natural and human-managed land cover.

As a result, researchers have become increasingly eager to collaborate and produce sophisticated modelling strategies. This to the aim of (i) bringing together economical with physical and spatial characteristics of land; (ii) reconnecting the global with the regional dimension of land use; (iii) investigating feedbacks amongst the land, the economic and the Earth systems; and (iv) assessing the implications of land-use change for climate policies. In this direction moves the effort of those researchers involved in the development or enhancement of Integrated Assessment and Earth System models, as well as impact assessment frameworks. In this context, land-use change has been identified as one of the main examples of potential human–physical system interactions for which tighter linkage of Integrated Assessment and Earth System models is most desirable [7].

After summarizing the state-of-the-art modelling for the land system and its feedbacks, this paper provides a critical discussion on key aspects in the field. It presents a broad, updated, and comprehensive picture of the existing frameworks. The critical comparison of characteristics, strengths and limits of commonly used approaches is intended to promote advancements in the modelling design of LULUCF activities.

Clearly, the ambition of this article is not to describe the complete sample of existing models or methodologies rooted in a vast number of disciplines. This would require the development of a much-extended research, going beyond the length of this manuscript. The attention is restricted to agriculture and forestry, the two land covers to which almost one-third of global greenhouse gas (GHGs) emissions can be associated [8,9]. Readers interested in deepening their knowledge are invited to refer to specific studies (see, for example, [10] for exploratory land-use studies and their role in policy [11,12] for land use related to economic-based deforestation, [13] for a general review of the literature, [14] for land-use models based on economic theory, [14,15] for spatial and economic classifications of models, [16,17] for models of agricultural intensity, [18] for spatial, temporal, and human decision-making dimensions, [19] for Agent-Based Systems, [20] for mainly descriptive models, [21,22] for partial and general equilibrium models, [9,22] for continental and global land-use models, and [23] for econometric forest sector modelling in Europe).

The structure of this work is as follows. Section 2 draws a model categorization, which guides transverse considerations on major features, strengths, and concerns of existing frameworks. A critical review of the most relevant geographical, economical, and integrated frameworks is then provided in Sections 3–5. The final section concludes offering hints for future research.

2. Modelling Land and Its Feedbacks: Different Approaches to Dealing with the Same Problem

The complexity of modelling LULUCF has brought a broad variety of approaches into production. Most models are different in terms of methodologies, purposes, assumptions, geographic areas of the analysis, and both the source and type of data used. The objective of integrating the socio-economics, the climate component, and the spatial dimension of LULUCF, often implying developing combinations of dissimilar models used simultaneously, has further complicated the overall picture.

As a result, restraining models in a rigid classification would not reflect the numerous dimensions that normally characterize most of them (purpose, type of data, regional aggregation, *etc.*): one model can be global, economic, statistical, prescriptive, *etc.*, at the same time. However, it is useful to consider some classifications to guide a more organized discussion on the modelling aspects of major interest.

A first possible distinction is between standalone and linked/integrated models. While standalone models focus either on "geographic-biophysical" or on the economic aspects related to the land system, model linkages or integrated frameworks design an interaction of these model classes.

To these macro-categories belong very different approaches that, historically, have been developed to address dissimilar research questions, though all are related to the common field of the "land system" representation. For example, within standalone models, geographical-oriented frameworks favor the representation of land-cover change. Climate-related aspects are normally included in the analysis and drive results, though they are typically assumed as exogenous to the system and leave no room for feedbacks between the land and the climate spheres. Economic-oriented frameworks focus on agents' behaviors and price/rent driving mechanisms. They may envisage some "economic" feedbacks and favor a better representation of land-use, rather than land-cover change. They may account for some climate information, though indirectly, and disregard feedbacks between the climate and the land system.

Although the words of land cover and land use are commonly (yet, erroneously) used interchangeably, they are conceptually different. Land cover is physically designed and relates to vegetation (natural or artificially modified) and its structure, and to other land types covering terrestrial land. Land use is anthropogenically designed and relates to the purpose the land serves. It depends on the way humans manage the landscape, on decision-making processes and policy, and on society behavioral changes. It responds to economic drivers such as food and energy prices, timber prices, and land rents. The relation between the two is such that one land cover may have multiple land uses, and land use affects land-cover change. This distinction clarifies why geographical and economic-oriented models are more apt to capture, respectively, land-cover and land-use change.

Finally, linked or integrated models put more effort in creating a connection between the land system and relevant economic and physical components, offering a better proxy of the real-world functioning mechanisms. Examples are Integrated Assessment Models (IAMs) and Earth System Models (ESM). The first typology frames human decisions on land use and management and usually accounts for climate in a simplified way. The second represents the global climate and the carbon cycle on a more physical basis, resolving the regional features while neglecting the human component of the land system.

Interestingly, the way in which these two integrated frameworks look at the world roughly reproduces that of geographic and economic-oriented standalone models. Indeed, even recognizing IAMs and ESMs advancements in tackling specific issues of standalone models, their integration mostly occurs via a carbon-cycle component only, and their view remains focused either on anthropogenical or on physical processes. However, all research groups have recently acknowledged the need of modelling the land system and its feedbacks with climate and the economy in a more combined fashion such that communication and collaboration amongst scientists has increased. Table 1 summarizes major characteristics of the broad model categories.

Table 1. Main general characteristics of the modelling categories. Source: Own Elaboration.

	Strengths	**Limitations**
Geographic/ Land-Cover Models	Spatial dimension of land-use change; Biophysical constraints on land-use change.	No endogenous economics; No endogenous land-use change; No global analysis; No feedbacks with climate nor with the economic system.
Economic/ Land-Use Models	Endogenous land allocation mostly based on economic theory; Opportunity costs explicitly considered; Consideration of markets interactions.	No spatial assessment; No physical constraints or biophysical land characteristics; Land-use allocation entirely driven by market structure. No feedbacks with climate nor with biophysical aspects of the land system.
Model Linkages	Economy linked with biosphere and atmosphere in a unique framework; Ability to account for feedbacks amongst human and physical systems. Synergies and trade-offs of different policy strategies; Long-time scale analysis.	High complexity and demanding for computer power; Sacrifices a detailed representation of land processes; Linking models maintain details but require much harmonization to reach convergence; Difficult to perform uncertainty analysis.

In following sections, more details are offered about research objectives and skills of each approach. To this aim, the comprehensive macro categories are further broken down in classes that are more specific. The complete list is presented below:

Standalone Models

A. Geographical/land-cover models

   a. *Statistical models*
   b. *Rule-based models*

B. Economic/land-use change models

   a. *Econometric models*
   b. *Partial equilibrium models*
   c. *General equilibrium models*

Model Linkages and Integration

C. Linked or integrated models

   a. *Earth System Models*
   b. *Integrated Assessment Models*

It is noteworthy that the diversity of models based on first principles, or trying to represent biogeochemical and biophysical components of the land system, is much smaller compared to that of the economic-oriented frameworks. For example, advancements in climate and Earth system models are developed by parallel or integrated efforts of the main modelling groups of the world. This is not the case with economic or integrated assessment models. Indeed, interpreting and modelling current and future human behavior and socio-economic changes entails, to a certain extent, higher degrees of freedom in terms of assumptions and available modelling approaches. As a result, there is a wider variety of models focused on the human component of the land system compared to the Earth system or land surface models described in following sections. This is reflected in this manuscript.

3. Geographic/Spatial Frameworks for Land-Cover Change Analysis

Broadly speaking, geographic/land-cover analyses have been supported by the rapid improvement of remote sensing and Geographic Information Systems (GIS). Land cover is typically determined by analyzing satellite and aerial imagery. The spatial dimension and the geographical/physical aspects of the land problem are central to this type of analysis. Regional or large-scale assessments represent the majority of existing exercises. Examples of geographic models for land-cover analysis are CLUE [24] and Dyna-CLUE [25], ELPEN-System [26], SALU [27,28], EFISCEN [29], ACCELERATE [30], MedAction [31], and KLUM [32], among others. These models can be developed for large [30], regional [26–28,33–38], or global [32] scale analysis. Table 2 reports major features of some of them.

Table 2. General characteristics of some geographic frameworks.

Model Name	Type of Model	Nature of Model	Land-Use Type	Geographic Scale	Dynamics Technique	Temporal Dimension
KLUM [32]	Optimization model/Rule-based model	Geographic model; allocation rules based on profit maximization	Agriculture	Global	Static	Base year 1997; Analysis 1997–2050
ACCELERATES [30]	Optimization model/Rule-based model/IAM	Geographic model: allocation rules based on profit maximization	Mainly agriculture	Macro-Regional or other local areas	Comparative static	Analysis 2000–2050
CLUE [24,25,33–38]	Statistical/Simulation Model	Geographic model	Multiple land-use types	Regional areas	Systems dynamics model/ statistical techniques	Several decades' analysis-20–40 years.
ELPEN-System [26]	Statistical/Simulation Model	Geographic model	Agriculture-Livestock sector	Europe	multiple linear regression model	Base year: 1997 and 2000
SALU [27,28]	Rule-based model	Geographic model	Agriculture	Sahel area	Dynamic simulation model	Up to some decades of analysis

Two broad model categories can be distinguished: statistical and rule-based models. In statistical models, land suitability and allocation derive from either empirical or statistical verification. It is the result of a combination between a top-down approach, where land use mostly depends on exogenous macroeconomic factors, and a bottom-up approach based on locally specific processes of vegetation dynamics. Few economic drivers are considered—typically involving the demographic expansion and the GDP rate of growth - which are not endogenously integrated in the system. They can represent one (ELPEN-System) or several land-cover types (CLUE).

Alternatively to the empirical or statistical verification, land-cover analysis can be based on decision rules resulting from an agents' profit maximization problem (ACCELERATE, KLUM), from specific studies (SALU, EFISCEN) or from subjective judgments (MedAction). In this latter case, the extent to which these expert considerations can be extended to large areas remains arguable. Compared with statistical frameworks, rule-based models address more explicitly the interactions between land-use processes and driving factors. They can capture the effects of new land-use policies and can incorporate different drivers for future land prediction. Nevertheless, with statistical models they share the lack of endogeneity of land allocation: influential factors (socio-economic, environmental, and others) are assumed exogenous to the system. Similarly to statistical models, they can focus on one (EFISCEN, SALU) or more land-cover types.

Despite the effort of integrating economy and biophysics, the model structure of statistical and rule-based models remain that of a geographic model, more apt to analyses land-cover rather than land-use change in time. They do not fully account for the underlying economic aspects of land use, nor do they involve responses of consumption and production to changes in prices. The lack of an endogenous categorization of land-use change normally does not foresee a role for feedback effects.

4. Economic Frameworks for Land-Use Change Analysis

Economic models are based on the traditional economic theory and aim at explaining changes in land-use patterns with changes in economic variables (e.g., production and consumption, prices, *etc.*). They can be classified into (i) Econometric models and Ricardian Analysis; (ii) Optimization and Equilibrium models.

4.1. Econometric Models and Ricardian Approach

Econometric models estimate the opportunity cost of land and carbon-sequestration costs by analyzing landowners' historical decisions—revealed preferences—on land-use allocation. They investigate the relation between choices on land allocation and market price differentials (for instance, for crops and timber products). By deriving a response function this approach allows simulating how landowners would react under similar or different policy scenarios (such as a governmental subsidy to forest-carbon sequestration) [39–43].

In general, the interest in implementing an econometric approach lies on its flexibility and on the simple way in which (i) it is possible to account for a variety of factors affecting land opportunity costs; (ii) it incorporates changes in land quality and landowners' preferences. However, this methodology is susceptible to some critiques. First, it normally neglects the role of technology and sometimes of climate variability. Secondly, the assumption that driving factors are exogenous is sometimes odd. Indeed, statistical problems of endogeneity, collinearity, and reverse-causality often arise with respect to many explanatory variables (population growth, prices in the long-run, *etc.*), undermining the unbiasedness or the efficiency of the estimates [23,44–46]. Third, this approach is often developed within a short-run analysis and small sample sizes, which results in a low degree of explanation [20]. Furthermore, the regression techniques typically implemented leave no scope for a comprehensive understanding of the interactions between underlying drivers, processes and their relations, which are frequently considered constant in time. These aspects call for a careful analysis of the results, especially for long-run simulations [9].

A parallel method is the so-called "Ricardian approach" which has been successfully applied since the early 90s [47–51]. It generally presents the form of a cross-sectional analysis, which aims to measure the impacts of a changing climate on landowners' choices. Despite its greater focus on climate variability with respect to traditional econometric approaches, its one-year data analysis is likely to produce unstable results [52]. In addition, inter-annual changes in weather, normally used as a proxy for intertemporal climate variation is unlikely to be forecasted by farmers and therefore result in a poor surrogate for climate change, to which landowners can better adapt [53]. The latest advancement of this methodology intends to address these issues developing a panel study analysis, more appropriate to register farmers' choices on land-use in time. Despite the answers given to these concerns, the Ricardian approach as well as the traditional econometric approach can still be claimed to develop regional rather than global analysis, which makes it difficult to scale-up resulting outcomes.

Because of the lack of endogenous treatment of forces driving changes in land, both econometric and Ricardian approaches do not foresee any feedback effect, neither physical nor economical.

4.2. Equilibrium Approaches. A General Overview

Equilibrium models are commonly employed to assess impacts of land-use change. They are able to evaluate the effect of different land-use policies capturing trade-offs amongst the opportunity costs of alternative land-based mitigation strategies, price and trade dynamics as well as other economic interactions among sectors and/or regions. They maximize individual/regional welfare or firms' profits under some constraints on budget, natural resources or technology. The solution derives from equating demand and supply for either land-using sectors (partial equilibrium models or PEMs), or the economy as a whole (general equilibrium models or GEMs). The equilibrium of the system can be either static or dynamic as well as competitive, or non-competitive. Dynamic frameworks can be distinguished into recursively-dynamic and forward-looking models, depending on the type of equilibria and assumptions on agents' expectations.

Land is generally conceived as one input to production and is treated as a regional and non-tradable endowment, assumed fixed or not extendable to economically inaccessible areas. This impedes capturing effects such as the contraction of agricultural land resulting from, e.g., urbanization.

In addition, traditionally, an initially aggregated land endowment is broken down into different land-use types via a "nested" Constant Elasticity of Transformation (CET) function [54]. This approach allows allocating land as a function of specific elasticity parameters (calibrated or estimated with econometric techniques) which govern the response of the land supply to changes in relative prices and rents. As a result, the outcomes are sensitive to changes in parameters and functional forms assumptions. In addition, while model validation can help to provide support to the robustness of results [55,56], few attempts propose historical counterfactual analysis. Also, individuals and firms are modelled as representative agents within, respectively, one region and one market sector. Unless an assortment of different representative households and firms is modeled, this implies assuming the same socio-economic preferences across the world and across economies for what it concerns, such as land management practices and land-related preferences.

4.2.1. Partial Equilibrium Models (PEMs), Some Examples

In PEMs, production and consumption respond to price variations, which adjust to achieve the equilibrium between demand and supply for land-using commodities only. Having a bottom–up structure, partial equilibrium models have the advantage of describing land management and its changes with a good level of detail, allowing an in-depth analysis of the land-use markets. Nevertheless, by only representing land-using sectors, they disregard all the feedbacks deriving from the rest of the economy. On the other hand, their detailed bottom-up specification, along with their simple market structure, make these models particularly attractive for combining with other optimization or equilibrium approaches (e.g., GEMs). Similarly, they are sometimes included in the larger structure of an Integrated Assessment Model (IAM). Examples of PEMs include WATSIM [57], CAPRI [58], and CAPRI-Spat [59], AgLU [60,61], IMPACT and IMPACT-WATER [62], FASOM [63,64], GLOBIOM [65], and the GTM model [66,67]. Their focus can be on the agriculture market (IMPACT, WATSIM), the forestry sector (GTM) or both (AgLU, FASOM, GLOBIOM). In the latter case, they are able to capture competition in land across different uses. They can work at either global (WATSIM, GTM) or regional scale (CAPRI and CAPRI-Spat are developed for Europe while AgLU and FASOM for US) and their equilibrium structure can be either static (CAPRI, IMPACT) quasi-dynamic (WATSIM, GLOBIOM), or involve a more complex intertemporal–perfect foresight construction (FASOMGHG).

4.2.2. General Equilibrium Models (GEMs), Some Examples

Compared with the partial equilibrium models, GEMs represent the overall economic system, not only land-using sectors, providing a more comprehensive analysis of the dynamics of production and prices. Originally, only one homogeneous land type, completely characterized by the agricultural sector (cropland and grazing land), was in use. In addition, changes in agricultural land were measured as the value-added to production rather than in physical units of area (GTAP-L is the only exception), neglecting the spatial dimension of land distribution [9]. Most importantly, changes in land uses were modelled as independent from climatic variability or soil constraints and their role in influencing land differences and productivity changes across space and time was neglected. Examples of such CGE models are GTAP [68]—which is the original structure upon which most of todays' CGE models are based—GTAPE-L [69,70], GTAPEM [71,72], GTAP-AGR [73], G-cubed for US [74], and ICES [75].

Table 3. Main characteristics of equilibrium approaches.

Model Name	Type of Model	Nature of Model	Land-Use Type	Geographic Scale	Dynamics	Temporal Dimension
FASOM-GHG	PEM	Economic model	Agriculture, Forestry, Grazing. Good treatment of forestry	USA in 11 regions	Dynamic-perfect foresight, nonlinear programming	Base year: 2000. 10 yr time step. 10-yr analysis
WATSIM	PEM	Economic model	Agriculture	Global: 9 regions	Quasi-dynamic model. No price expectations	Base year: 2000 5 yr time step
GTM	PEM	Economic model	Timber sector	Global: 12 regions	Intertemporal optimization with perfect foresight	1 yr time step; Analysis 1990–2140
IMPACT-Water	PEM	Economic model	Agriculture	Global: 36 regions	Comparative static	Base year: 2000. 1 yr time step. Analysis in 2020/2025/2050
AgLU	PEM	Economic model with focus on land use	Agriculture, Forestry, Grazing	Global: 11 regions	Comparative static	Base year: 1990. 15 yr time step. Analysis 1990–2096
CAPRI and CAPRI-DynaSpat	PEM	Economic model	Agriculture	EU15-EU27	Comparative static, solved by iterating supply and market modules	Base year: 2002. 5–10 yr analysis. Specific cases of 20 yr analysis scenario
GLOBIOM	PEM	Economic model, good focus on land use	Agriculture, Forestry, Livestock, Bioenergy production	Global: 11 or 27 regions	Recursive Dynamic	Base year: 2000; Analysis up to 2030, 2050. 10 yr time step:
GTAP	CGE	Economic model	Agriculture	Global: latest version (GTAP7) accounts for 113 regions	Comparative static	Max 50 yr projections
G-cubed	CGE	Economic model	Agriculture	Global:12 regions	Dynamic	Analysis 1993–2070 in 1 yr time step
GTAPE-L	CGE	Economic model	Competition among different land uses: agriculture, forestry and other sectors	Global: 5 regions	Comparative static	Base year: 1997
GTAPEM	CGE	Economic model	Agriculture	Global: 7 regions	Comparative static	Base year: 2001. Analysis: 2001–2020
GTAP-AGR	CGE	Economic model	Agriculture + explicit substitution amongst feedstuff in livestock	Global: 23 regions	Comparative static	Base year 1997

Table 3. *Cont.*

Model Name	Type of Model	Nature of Model	Land-Use Type	Geographic Scale	Dynamics	Temporal Dimension
BLS-IIASA	CGE	Economic model	Focus on agriculture and pastureland	Global: 34 regions	Recursive dynamic	Base year 2000. 1 yr time step
GTAP-AEZ	CGE	Economic model	Agriculture, Forestry, Grazing	Global: 3 regions	Comparative static	Base year: 2001. Max 50 yr projections
GTAP-Dyn	CGE	Economic model	Agriculture, Forestry, Grazing	Global: 11 regions	Recursive Dynamic	Base year: 1997; Analysis: 1997–2025.
AgLU2x	CGE	Economic model + mapped watersheds	Agriculture, Forestry, Grazing	USA in 18 regions	steady-state comparisons consistent with an intertemporal model for forestry	Base year: 1990 Model in steady state
ICES-AEZ	CGE	Economic model	Agriculture, Forestry, Grazing	Global: 13 regions	Static Comparative Exercise	Base year: 2001 Analysis: 2001–2025.
MIT-EPPA	CGE	Economic model	Agriculture, Forestry, Grazing, Bioenergy production	Global: 16 regions	Recursive Dynamic	Base year: 1997; Analysis: 1997–2100; 5 yr time step
BLS-IIASA	CGE	Economic model + agronomic-based datasets	Agriculture, Forestry, Grazing, Bioenergy production	Global: 34 regions grouped in 11	Recursive Dynamic	Base year: 2000; Analysis: 1990–2080. 10 yr time step

As soon as the recent global Agro Ecological Zones (AEZ)-database for land-use emissions and forest-carbon sequestration [76] was released, the assumption that land is homogeneous and perfectly substitutable among different uses and sectors was progressively relaxed. In the new database, physical and economic information (land hectares, land rents for forestry, agriculture, and livestock) is allocated into different AEZs. Each AEZ implies different acreage characteristics due to climatic conditions and soil features. Framework based on this new database are, for example, GTAP-AEZ [76–78], GTAP-AEZ-GHG [6,79,80], and ICES-AEZ [81]. Recent attempts have converted the static nature of these models into a recursive dynamic framework [82,83] or extended the running period up to the year of 2080, as in the coupling experiment between the IIASA-FAO AEZ model and the BLS CGE framework [84].

Table 4. Geographic and economic sub-categories: comparison.

<table>
<tr><th></th><th></th><th></th><th>STRENGTHS</th><th colspan="2">LIMITATIONS</th><th>Examples</th></tr>
<tr><td rowspan="2">GEOGRAPHIC MODELS</td><td colspan="2">Statistical models</td><td>Multiple land-use drivers considered;
Multiple land-cover types considered.</td><td rowspan="3">Driving factors assumed exogenous;
Not endogenous land allocation or climatic change;
Very limited feedback effects, if any.</td><td>Normally short-run and non-global analysis.</td><td>CLUE and Dyna-CLUE, ELPEN</td></tr>
<tr><td colspan="2">Rule-based models</td><td>More explicit assessment of land processes and drivers w.r.t. Statistical Models;
Multiple rules considered;
Multiple land-cover types considered.</td><td>Rules based on subjective judgments.</td><td>SALU, EFISCEN, ACCELETATES*, KLUM*</td></tr>
<tr><td rowspan="4">ECONOMIC MODELS</td><td rowspan="2">Econometric models</td><td>Econometric</td><td>Multiple land-use drivers;
Multiple land-cover types considered;
Agents' reactions under similar or different policy scenarios.</td><td>Technology and climate variability not always considered; Need to deal with problems of endogeneity and reverse causality; normally short-run, local and small sample analysis.</td><td>Stavins [39], Plantinga and Mauldin [40], Lubowski et al. [41], Pfaff et al. [42], Munroe and Muller [43]</td></tr>
<tr><td>Ricardian Analysis</td><td>Multiple land-use drivers;
Multiple land-cover types considered;
Greater focus on climate variability w.r.t. Econometric Models;
Recently extended to panel-data analysis.</td><td colspan="2">Ignore technology change;
No global analysis;
Very limited feedback effects.</td><td>Sanghi and Mendelsohn [49], Mendelsohn and Dinar [50]</td></tr>
<tr><td rowspan="2">Optimization and Equilibrium Approaches</td><td>Partial equilibrium models</td><td>Multiple land-use drivers;
Agents' reactions under similar or different policy scenarios;
Good detail in land-using markets;
Land allocation endogenously derived w.r.t. Econometric and Ricardian Analysis, so that economic feedbacks are accounted for;
Often global and forward-looking models.</td><td colspan="2">Only a part of the economy is modelled and represented;
Models not frequently validated;
Agents' preferences on land allocation assumed to be the same;
Climate and biophysics have rarely a time-variant impact on land differences and productivity;</td><td>CAPRI, IMPACT-Water, WATSIM, AgLU, FASOM, GTM, GLOBIOM°</td></tr>
<tr><td>General equilibrium models</td><td>Agents' reactions under similar or different policy scenarios;
Compared with Econometric and Ricardian Analysis, land allocation among land covers endogenously derived;
Compared with Partial Equilibrium Models all the economy is considered;
Global scale investigations.</td><td colspan="2">Land exclusive input for agriculture, represented as value added to production;
Normally, only currently managed land is represented: land is not allowed to expand;
Less detailed production description compared with Partial Equilibrium models;
Identical agents' preferences on land allocation within regions and sectors;
Climate and biophysics have normally no impact on land differences and productivity.</td><td>G-cubed, GTAPE-L, GTAPEM, GTAP-AGR, GTAP-AEZ, GTAP-Dyn, AgLU2x</td></tr>
</table>

*Geographic model with economic considerations.

Disaggregating land according to the agro-ecological approach implicitly assumes time invariant land qualities (reflecting differences in climate, soil conditions, length of growing periods, and therefore productivity). An alternative approach to Agro Ecological Zoning derives from enhancing the AgLU model [85]. With AgLU2x the original framework is converted into a multi-sectoral general equilibrium model for US, divided into 18 watersheds. The advantage of using watersheds is twofold. Since they are expressed in physical units and are fixed in location, they can be spatially mapped to soil and give an important indication on land productivity. Along the same lines the recursive-dynamic EPPA framework in its 4th version [86] allows a spatial disaggregation of a good number of GHGs gases, aerosol, and other air pollutants. Indeed, being developed to become a component of the IGSM structured framework (see Section 5.2), the EPPA model involves an enhanced treatment of physical flows and stocks of emissions and land use, which favor linkages with earth system models (see Section 5.1). In the same way as BLS and G-Cubed, EPPA handles a long running period (up to 2100). For these reasons, EPPA and AEZ-based model represent examples of a hybrid economic and physical accounting model. They go beyond the traditional scope of a pure CGE economic model by seeking integration and consistency between economic and physical variables. Turning typical monetary economic values into physical quantities is an essential step towards the accounting of impacts and feedbacks between the environment and the economy. Similarly, climate analysis should connect changes in the biological and physical environmental variables of the earth system with the underlying economics. On this regard, the paragraphs following Table 3 (summarizing equilibrium models characteristics) and Table 4 (offering a general overview of geographic and economic models) explain and report different integration efforts and attempts.

5. Model Linkages

Several applications aim to describe the land-use system by using more than one model. Advanced model linkages are interdisciplinary settings where major features of society and economy are integrated with the biosphere and the atmosphere, in a unique framework. They allow complementing different information sources and combining the strengths of existing models and approaches.

Specifically, integrated frameworks entailing a high level of complexity are normally composed of sub-modules, communicating through the exchange of data and results. The sub-models can be added or removed depending on the specific research question that needs to be tackled. As a result, among their most relevant strengths high-complexity model linkages may have the ability to explicitly consider climate change, as well as the economics and biophysics of the land system. Compared to standalone models their structure makes it easier to explain feedback mechanisms amongst the different modules, to understand both drivers and impacts of land-use and land-cover change, to address the synergies and trade-offs of different policy strategies, to develop investigations with a global coverage, and to run long-time scale analysis. On the other hand, they entail a big degree of complexity and are demanding for computer power. Such complexity and inter-linkages among different models also make the analysis of uncertainty very difficult [7]. The development of global-to-regional land-use assessments remains an on-going process still seeking to fully tackle some methodological barriers faced by standalone models. Broadly speaking, to this category belong both the Earth system and the Integrated Assessment models.

5.1. Model Linkages with Focus on Biophysical and Biogeochemical Processes; Climate and Earth System Models

Climate and Earth system models are developed with the primary effort of respecting first principles of physics, where possible. However, apart from specific aspects such as pressure gradient force, advection, gravity, *etc.*, the remaining physics, chemistry and biology are parameterized based on observations and experimental measurements, used as constraints. In a similar way to IAMs and socio-economic-oriented models, where a great number of coefficients and functions are in place, observations and measurements can represent a limited set of processes actually taking place in the real climate system [87]. Uncertainties related to the physical parameterization and the numerical implementation need to be characterized. In fact, given the complexity and the non-linearity of the involved physical and biological processes, but also the necessity of implementing them with limited computer power, large disagreement among the results motivates the need of performing investigations based on ensembles of simulations, rather than single realizations [88].

Climate and Earth system models can be categorized as an historical legacy of advancements that are developed by parallel or integrated efforts of the main modelling groups of the world, or by sharing. As a result, in terms of model structure, there exist a limited diversity of climate models compared to socio-economic frameworks and IAMs. This explains the more extended length of those sections devoted to the description of models belonging to the socio-economic dimension, relative to that related to climate and Earth system models. On the other hand, the concept of model ensembles is becoming popular within the IAM community as well, and the number of commonly accepted and used IAMs is shrinking.

5.1.1. First-Generation Land Surface Models

Land surface models (LSM) have been implemented in the general circulation models (GCMs) and in the regional climate models (RCMs) in order to provide a realistic representation of the climatic variables in the interface between land and the atmosphere, where people live. Therefore, they are the main model component potentially related to land-use variations.

The first generation of LSMs is characterized by a simple formulation for the fluxes of momentum, heat and water mass without an explicit representation of vegetation or the hydrological cycle, and a very limited representation of the geographical and sub-grid spatial heterogeneities. First LSMs attempts prescribe albedo and soil wetness through external data and neglect the soil heat storage [89].

As soon as latent heat fluxes were recognized as factors affecting the atmospheric hydrological cycle, a dynamical representation of soil moisture was introduced in a simplified manner through the so called “leaky bucket model” [90]. This model included water storage in the soil with a prescribed field capacity (constant everywhere). Soil water is allowed to accumulate until a certain value, above which precipitation in excess of evapotranspiration is converted into runoff.

5.1.2. Second-Generation Land Surface Models

The second generation of land surface models was essentially developed by Deardorff [91]. He included the plant canopy in the radiative fluxes and distinguished between the evaporative fluxes of intercepted water by the canopy, soil evaporation, and plant transpiration, by introducing the concept of stomata resistance, as well as a representation of the vertical temperature and moisture gradients within the soil. In fact, given the relatively coarse horizontal resolution of these implementations, climate modelers focused in achieving an accurate reproduction of the vertical fluxes and ignored the horizontal inhomogeneities and the related water movements, in opposition with the traditional hydrological models. However, this model generation accounted for the effect of land-cover distribution and snow in the surface fluxes and soil dynamics. The Biosphere–Atmosphere Transfer Scheme (BATS, [92]) and the Simple Biosphere Model (SiB, [93]) are notable examples of second-generation LSMs. In addition, they considered the horizontal distribution of the different "plant functions types" (PFTs) affecting the surface fluxes. PFTs are defined as broad categories of vegetation sharing similar features e.g., grasses, broadleaf and needle leaf, evergreen and deciduous plants, and crops. PFTs are treated in these models as collections of parameters affecting the computation of the heat budget and the hydrological cycle, as albedo, roughness, leaf area, stomata resistance, root depth, and other parameters depending on the particular model. They also accounted for the different soil types determining thermal and hydraulic properties such as heat capacity, thermal conductivity, porosity, hydraulic conductivity and suction.

The second-generation models often considered stationary land-cover and land-use spatial distribution, derived from satellite products [94]. These models were widely used to study the biogeophysical impact of vegetation on climate by altering artificially the PFTs distribution, but with any economical constraint. The pioneering study of Charney *et al.* [95] on the dynamics of deserts is one of the most notable examples of such studies [96]. Following classical and recent idealized experiments, based on such land-surface models, consisted in studies investigating biogeophysical feedbacks that did not involve carbon cycling and budget. In particular, they focused on the effects of global afforestation/deforestation of evapotranspiration, albedo and surface roughness on surface temperature, on the water cycle and on the atmospheric circulation [97,98]. The climate of a total deforested world would be about 1 K cooler [97]. Therefore, as a matter of fact, these biogeophysical forcings have an important impact on climate and can potentially exert, in particular areas, a stronger effect than biogeochemical forcings, (e.g., greenhouse gas emissions) [99].

However, regional effects of deforestation are characterized by strong spatial variability so that they can result in either cooling or warming. Primary feedbacks of vegetation changes to climate are well understood in the tropics, where afforestation/deforestation increases/decreases surface roughness and evapotranspiration, cooling/warming the surface [97,100]. In the high latitudes, the opposite effect is found because the surface energy budget is dominated by the changes in albedo through the masking effect of vegetation on snow [97,101]. In the middle latitude, some consensus exists on the cooling effect of deforestation in favor to cropping land-use [98]. However, the magnitude and the sign of the feedback on surface temperature are more uncertain with respect to the tropics and the sub-polar regions. In fact, the relative importance of the counteracting effects of albedo and evapotranspiration changes, on surface temperature, is region-specific and depends on the model adopted [98,102–105]. Global deforestation results in a weakened water cycle over land, consisting of reduced precipitation and evapotranspiration and increased runoff to the oceans [106].

5.1.3. Dynamical Global Vegetation Models and Third-Generation Land Surface Models

Dynamical Global Vegetation Models (DGVM, [107,108]) were developed in order to account for the temporal variability of natural PFTs spatial distribution because of establishment, survival and competition resulting from climate and atmospheric CO_2 change. They account for crop PFT in terms of the local biogeophysical and biogeochemical effects [109]. DGVM are often integrated in the third generation of LSMs, which were developed in response to the needs of including the carbon cycle in Earth System Models (ESMs) and that of accounting for the complexity of land surface processes. The stomata resistance determining plant transpiration is linked to a quasi-mechanistic model of photosynthesis that explicitly represent the CO_2 fluxes between land ecosystems and the atmosphere [110,111]. Currently, most advanced models entail a fully prognostic treatment of carbon and nitrogen cycling in the terrestrial ecosystems, including the interactions mediated by plants, whose phenology depends on each PFTs, and soil heterotrophs [112,113]. However, crop distribution is stationary in these models and land-use changes can be prescribed only using external results from IAMs, as it is done in the recent IPCC Fifth Assessment Report (AR5, WGI). Of course, the effects of land-use changes are expected to be comparatively smaller than the effects of global deforestation/afforestation experiments. However, there are observational evidences that suggest a significant local effect that needs to be quantified [114–116]. In fact, historical deforestation is responsible for a significant albedo increase in the mid-latitudes [117]. While the relative magnitude of CO_2 and albedo effects remains uncertain, the historical land use pattern is found to be biased towards stronger CO_2 and weaker albedo effects as compared to idealized large-scale deforestation, resulting in a global warming when the biogeochemical effect of land-use changes (e.g., increased CO_2 in the atmosphere) is considered [118]. Even larger warming can be expected as a positive combination of biogeophysical and biogeochemical effects due to the current land-use change which is concentrated into tropical deforestation and stabilization of historical mid-latitude deforestation [119,120].

Most of the models included in the IPCC AR5 assessment consider prescribed land-use changes [121]. They are listed in Table 5, extracted from the IPCC preliminary documents currently available on the IPCC Fifth Assessment Report, contributing on carbon cycle assessment in the context of climate change. Table 5 highlights the principal differences amongst land surface models [122–132] in terms of (i) numbers of PFTs considered; (ii) treatment of the natural PFT relative to dynamical land-cover changes; and (iii) treatment of nitrogen limitation of plants growth and fires, which may be natural or anthropic.

As in previous generation models, these implementations account for the anthropic influence on climate, in terms of biogeophysical effects on the surface-energy budget and hydrology. In addition, they can evaluate carbon-storing capabilities of the terrestrial ecosystems. Therefore, they can be used in order to compute the effective emission levels to be assumed as constraints in order to meet greenhouse gases concentrations imposed in future scenarios. On the other hand, they neglect greenhouse gas emissions associated to land-use change. Moreover, uncertainties exist in the interpretation of the land-use classes to be consistent with the PFT included in the various LSMs. This might involve several assumptions especially for the class of pastureland and the difference between primary and secondary vegetation, which, in fact, might complicate the interpretation of the results [133,134]. However, they include the effects of CO_2 fertilization in the modeled vegetation phenology that can exacerbate the regional scale effects of land-use changes in the context of the future climate [135].

Table 5. Characteristics of coupled climate models. Source: Own Elaboration from Table 6.11 in IPCC AR5 preliminary documents (WGI).

Model	**Modelling Center**	**Atmospheric Resolution**	**Land-Carbon**						**Reference**
			Model Name	**Dynamic Vegetation Cover?**	**No. of PFTs**	**Inclusion of Land-use Change**	**Nitrogen-Cycle**	**Fire**	
BCC-CSM1.1	BCC	~2.8°, L26	BCC_AVIM1.0	N	15		N	N	Wu *et al.*[122]
CanESM2	CCCma	T63, L35	CTEM	N	9	Y	N	N	Arora *et al.* [123]
CESM1-BGC	NSF-DOE-NCAR	FV 0.9 × 1.25	CLM4	N	15	Y	Y	Y	Long *et al.* [124]
GFDL-ESM2G	NOAA GFDL	2 × 2.5°, L24	LM3	LM3	5	Y	N	Y	Dunne *et al.*[125]
GFDL-ESM2M	NOAA GFDL	2 × 2.5°, L25	LM4	LM3	5	Y	N	Y	Dunne *et al.*[125]
HadGEM-ES	MOHC	N96 (~1.6°), L38	JULES	Y	5	Y	N	N	Collins *et al.* [126]; Jones *et al.* [127]
IPSL-CM5A-LR	IPSL	3.75 × 1.9, L39	ORCHIDEE	N	13	Y	N	Y	Dufresne *et al.* [128]
MIROC-ESM	MIROC	T42, L80	SEIB-DGVM	Y	13	Y	N	N	Watanabe *et al.* [129]
MPI-ESM-LR	MPI-M	T63 (~1.9°), L47	JSBACK	Y	12 (8 natural)	Y	N	Y	Raddatz *et al.* [130], Brovkin *et al.* [131]
NorESM-ME	NCC	1.9 × 2.5°, L26	CLM4	N	16	Y	Y	Y	Iversen *et al.* [132]

5.1.4. Brief Discussion on Models' Results and the Human Dimension in Land Surface Models

Most models report statistically significant cooling in near-surface temperature over regions for past land-cover change, while large uncertainties are reported on the evapotranspiration changes and no clear signal is identified for precipitation [136]. As for the future projection of the effects of land-use changes, some models reveal regional significant feedback in the surface climate, while the global effect is largely dominated by the fossil fuel forcing both in the present [137] and in the future climate [134]. It is noteworthy that land-use change were responsible for about half of the total CO_2 emissions up to 1950, while later it is dominated by the fossil fuel use [138].

All models included in the LUCID-CMIP5 experiments predict a loss in global land carbon storage in the future climate. In particular, the effects of land-use changes were analyzed in the context of two contrasting future scenarios: a business as usual (RCP8.5) and one in which an aggressive emission reduction policy is adopted in order to bound the Earth warming within about 2 K (RCP2.6). RCP land-use change scenarios developed by Hurtt *et al.* [121], seamlessly connects gridded historical reconstructions of land-use with future projections in a format required by ESMs while preserving as much information from the future scenarios as possible. As a main difference regarding future projections, RCP8.5 is characterized by wood harvest for biofuels and by a larger increase of pastures than the RCP2.6, which is characterized by a larger increase of crops. Most significant climatic signals due to land use with respect to the effects of the radiative forcings are found for the RCP2.6 scenario ([134]; [139] for a single model simulation driven by several land-use change scenarios). Although a large spread in the modelling results exists, most models agree on the sign of change: increase in temperature and decrease in precipitation due to lower evapotranspiration [134,140]. Land-use decisions will be critical for future land–atmosphere CO_2 flux [139].

The variety of potential feedbacks of land-use changes on climate (atmospheric temperature, humidity, cloud cover, circulation, and precipitation) are discussed in Kabat *et al.* [96], in the National Research Council report [141], and in a recent comprehensive review by Mahmood *et al.* [142], where also the effects-at-a-distance of the local land-use changes are highlighted. Moreover, land-use changes can affect also the occurrence of extreme events, not just the mean climate [143,144]. Consequently, the recognition of the complexity of human-caused changes needs to be taken into account in the afforestation-based mitigation strategies [145–147]. For instance, irrigation is an aspect of human-managed land-use that can exert strong forcings at the local scale which can be much larger than the effects of climate change [148] and entail important repercussions far from the region where irrigation is applied [149].

In a similar way to irrigation, there are other anthropic factors motivating the effort of including more and more sub-modules of the human dimension in the land-surface models. Advancement in terms of complexity include catchment hydrology [150]; lakes [151]; glaciers [152]; river-groundwater interactions [153]; biogeochemical processes affecting the composition of the atmosphere and, in turn, climate as dust mobilization [154]; biogenic volatile organic compounds emission from vegetation [155], and processes involving methane emissions [156]. Enhancements related to the socio-economic dimension of land use include urban land-cover modelling [157]; dynamical crop models interacting with the carbon cycle and including fertilization, land management [158]; water management [159]; irrigation [160,161], and natural, agricultural or deforestation fires [162]. This improvement in land surface models entailing the inclusion of different impacts and aspects related to the human dimension represent, in fact, a coupling strategy between some components of IAMs and others of ESMs [7].

5.1.5. Future Advancements in Earth System Models (ESMs)

Biogeochemical effects connected to land-use changes in ESMs are counted only in terms of the potential changes on the carbon storage capability due to the PFTs variations, as anticipated in the previous section. Therefore, the models need to be updated in order to compute the emissions of GHGs due to land-use changes. A general scheme, allowing the transitions between different cover types conserving carbon, also including transition from glacier and urban land cove types, would be desirable.

A better understanding of the implications in other aspects of the Earth system connected to the anthropic land use—as for instance the effect on the nitrogen and phosphorous cycles—is needed [163]. In this respect, the full coupling of the natural and anthropic induced carbon and nitrogen dynamics with the ocean biogeochemistry through the river transport is an interesting emerging field [96,164]. Currently, no ESM includes this important aspect. Regarding vegetation dynamics, even though it is acknowledged that disturbances (e.g., fires, pests, *etc.*) may significantly affect the response to climate change [165], their biomass implications are only rarely or partially considered [166]. In fact, there are evidences that the role of forests in providing the so-called ecosystem services should be emphasized in a more comprehensive view of the human forcings besides greenhouse gases [167,168], including also the loss of biodiversity and of the corresponding ecosystem resilience [169]. Finally, a two-way coupling between the climate and the atmospheric properties simulated by the ESMs and land-use change models is not yet uniformly considered. As a consequence of the traditional one-way approach, for instance, some of the integrations of the IPCC AR5 model are found to require negative GHGs emissions in order to be consistent with the imposed concentration scenario. This result can be considered unphysical, given the limited capabilities of the carbon sequestration techniques currently proposed. However, the effort of the climatological community to better represent complex biogeophysical and biogeochemical processes and relevant interactions for climate, have prepared the ground for a more concrete collaboration with Integrated Assessment modelers. Very recent and promising attempts of such integration, accounting for the complete feedback between natural and anthropic carbon cycling, are appearing [170] and would allow a consistent representation of the climate and social changes. On the other hand, climate model biases in temperature and especially precipitation still limit the potential integration of the impact models of the human dimension that often include threshold-dependent processes related to these climatic variables [88,171]. Therefore, model limitations must be carefully taken into account when considering the full IAM and ESM coupling.

5.2. Model Linkages with Focus on Socio-Economic Systems; Integrated Assessment Models

Integrated assessment models (IAMs) have had traditionally the aim of framing the integration between the human activity, the decision-making process, and the impact on the environment. Typical variables of interest are energy technology, good production and consumption, emissions of greenhouse gases, climate policy targets and costs. In time, a growing focus on emissions deriving from LULUCF has led integrated assessment modelers to represent more accurately the use of land for agriculture, forestry, pasture, and grazing along with the mechanisms driving land competition across categories and, therefore, land-use change. Within this framework, climate is often introduced in a simplified or reduced form and not always is fully integrated in the system. Also, the modelling of the global land-use system is less developed than the energy one [172]. However, the IAM modeler's community is making an increasing effort to advance the representation of land-related aspects [173]. Some of them are human behavior in forest investments and forest management, agriculture and forestry intensification and extensification, heterogeneous land endowments, pricing of unmanaged land, and competition in land between bioenergy and food production.

There exist several examples of IAMs, working closely with Earth system and ecosystem models to integrate the human decision components into natural processes. These include those models recently used to produce the harmonized land-cover scenarios for ESMs, as described in Section 5.3 below (*i.e.*, AIM, MESSAGE, GCAM, and IMAGE). The MIT Integrated Global System Model (IGSM) is perhaps one of the most complex integrated assessments designed to investigate human-driven global environmental changes and their effects on economy [87]. It involves components of both IAMs and ESM. It consists of the economic CGE model (EPPA, described in Section 4.2.2), a coupled atmosphere–ocean–land surface model, and natural ecosystems models.

Land-GHGs emissions and mitigation potential resulting from EPPA also depend on the climate change effects resulting from the Global Land System (GLS) framework [174] of IGSM. The GLS dynamically integrates the Community Land Model (which calculate global terrestrial balances for water and energy) with the Terrestrial Ecosystems Model (simulating carbon-equivalent contents in vegetation and soils) and with the Natural Emissions Model. This system, which develops the graphical distribution of land cover and plant "biodiversity" throughout the entire world, is linked with EPPA via the Terrestrial Ecosystems Model component. Table 6 offers more examples of integrated assessments linked with reduced form models for carbon cycle and atmospheric dynamics [175–189].

Future Advancements in Integrated Assessment Models

Amongst the possible areas of research where advancements are required for IAMs the following are perhaps the most relevant.

Concerning forestry, a future challenge for integrated assessment models will be to improve the endogenous modelling of future biophysical and economic implications of current investment decisions on forestland, as well as consequences on future mitigation paths. More effort should be put on modelling forestry intensification separately from extensification, and on representing non-market forest values. As for agriculture, among other aspects, IAMs should advance the representation of soil carbon abatement options, and the implications of fertilizer use. In addition, potential mitigation of the livestock sector should also be taken into account more extensively. Natural disturbances in agriculture and forestry should be better addressed. For example, forest and agricultural fires as well as their implications on reducing the potential for carbon sinks mitigation is normally neglected by IAMs.

Biomass production is a promising sector competing for land with agriculture and forestry. Its recent development entails the lack of historical data. Current studies can only poorly represent competition for land between food, biomass, and timber production. In years to come economic–climate models must attempt to improve these aspects by, for example, calibrating mitigation responses to estimates derived from progressively available econometric applications.

An improvement is also required in the identification and evaluation of the most important sources of uncertainty permeating IAMs within and across integrated modules. For example, incorporated energy-economic models, not precisely developed for land-use analysis, should confine uncertainty in parameters by using available econometric estimates or by calibrating outcomes to bottom-up approaches. In addition, uncertainty in fire incidences, pests and diseases in the agro-forestry sector would deserve more attention given their impacts on production, costs, and natural sequestration capacity.

Finally, we should not forget that the ultimate aim of IAMs is to assist decision-makers, providing them with relevant information on climate change impacts, policy options, related costs and consequences. Presenting technical and scientific model outcomes in a meaningful and understandable way remains a great challenge. In this respect, while uncertainties related to models and their results are well acknowledged among scientists, they represent difficult-to-digest information for policy makers. Reconciling science, policy, and practice therefore represents an important challenge ahead, requiring greater communication effort. Such a process should entail stakeholders' engagement whose knowledge could help remove barriers between science and policy.

Accounting for these issues in new generation IAMs models would significantly enhance future land demand and supply projections under baseline or under climate stabilization scenarios. This would result in a better estimation of mitigation amounts and costs, for both agriculture and forestry land-mitigation opportunities. In turn, enhanced estimations of future land demand and supply projection for each of the land-cover type would allow the production of more accurate harmonized land-cover scenarios.

Table 6. Characteristics of some Integrated Assessments linked with reduced form models for carbon cycle and atmospheric dynamics.

Model Name	Model Linkages	Land-Use Type	Geographic Scale	Dynamics Technique	Temporal Dimension	Models Interaction and Feedbacks	Reference
AIM	Global Climate model + GHGs emission model including a CGE	Multiple land-use types	Focus on Asia Pacific Region	Recursive-Dynamic	Run period: 1990-2100. Time step: 5 yrs	The CGE model is applied to quantify emissions from land-use change that feed the climate model. The climate model includes a simple carbon cycle module validated by dynamic vegetation simulations.	Matsuoka *et al.* [175]
ObjECTS-GCAM	Agriculture and land-use model (AgLU) + Integrated framework ObjECT (including GCAM reduced-form model for carbon cycle, atmospheric chemistry and climate change)	Multiple land-use types	Global: 14 regions	Recursive Dynamic	Base year: 1990. Run period: 1990–2095. Time step: 15 yrs	The climate model provides greenhouse gas concentrations, radiative forcing. In AgLU the link between changes in land use and land cover determine stocks and flows of terrestrial carbon.	Edmonds and Reilly [176]; Brenkert *et al.* [177]; Kim *et al.* [178]
IGSM-MIT	Economic module (EPPA) + model of atmospheric dynamics, physics and chemistry + an ocean model including carbon cycle and sea-ice + a set of coupled land models (the Terrestrial Ecosystem Model, the Natural Emissions Model, and the Community Land Model)	Multiple land-use types	Global: 16 regions	Dynamic model	Run period: 1990 up to 2250	The outputs of the combined anthropogenic and natural emissions models drive the coupled atmospheric chemistry and climate models. Climate model outputs, in turn, drive the outcomes of a terrestrial model on water and energy budgets, CO_2, CH_4, and N_2O fluxes, and soil composition. These results are fed back into the coupled climate/chemistry model	Sokolov *et al.* [87]

Table 6. *Cont.*

Model Name	Model Linkages	Land-use Type	Geographic Scale	Dynamics-technique	Temporal Dimension	Models Interaction and Feedbacks	Reference
IIASA model CLUSTER	PEM (GLOBIOM) + geographically explicit agent-based model (G4M) for forestry	Multiple land use-types for GLOBIOM but focus on forestry given G4M capability	Global: 11 regions	Dynamic model	Base year: 2000; Run period: up to 2030, 2050. Time step: 10 yrs	G4M informs GLOBIOM on biophysical vegetation growth and forest management cost. GLOBIOM gives results on endogenous commodity and land prices.	General reference: Gusti *et al.* [179]; G4M: Benitez *et al.* [180]; Benitez-Obersteiner [181]; Kinderman *et al.* [182]
IMAGE	Stand-alone softwares (TIMER energy model and FAIR emissions models) + IMAGE land-atmosphere model + agro-economic models (LEITAP-CGE and IMPACT)	Multiple land-use types but focus on agriculture and livestock	Global: 24 regions	Dynamic model	Run period: up to 2100; Time step: depending on sub-models but between 1 day and 5 yrs	Integration between terrestrial models (land cover and vegetation models), economic model, and a climate-ocean system. The terrestrial environment system calculates changes in land use and related emissions as a function of economic parameters. The vegetation model simulates crop productivities, distribution and natural vegetation according to climate and soil condition. Crop productivities are used in the land-cover mode to reconcile global land demand with supply.	Alcamo *et al.* [183]; IMAGE [184]; MNP [185]
WITCH-GTM	Integrated/Hybrid model and Optimization model & Partial Equilibrium model for forestry (2 economic models)	Focus on forestry	Global: 12 regions	Dynamic model	Run period: up to 2100.	WITCH feeds GTM with carbon prices while GTM gives in return carbon sequestration rates. These are included into WITCH carbon emissions balance and budget constraints.	WITCH: Tavoni *et al.* [186]; GTM: Sohengen and Mendelsohn [67]
WITCH	Integrated/Hybrid model and Optimization model	No explicit treatment of land use change	Global: 12 regions	Dynamic model	Run period: up to 2100. Time step: 10 yrs	The climate module feeds back into the economy via a damage function. Carbon dioxide emissions, produced by the economic activity, affect atmospheric concentration, radiative forcing, and temperature. In its turn, increases in global temperature translate into changes in regional GDPs.	Bosetti *et al.* [187,188]

Table 6. *Cont.*

Model Name	Model Linkages	Land-use Type	Geographic Scale	Dynamics-technique	Temporal Dimension	Models Interaction and Feedbacks	Reference
KLUM-GTAP	Rule based sectoral model for agriculture + CGE	Multiple land-use types but focus on cropland	Global: 16 regions	Dynamic model	Base year: 1997; Run period: up to 2050	The economic model informs KLUM on crop prices and yields. KLUM simulates land allocation, which is fed back into the economic model together with climate and soil impacts on yields.	Ronneberg *et al.* [55]
ICLIPS + AgLU	Integrated assessment (core ICLIPS) + PEM: land use model integrated into a climate-economy model and a carbon cycle module.	Multiple land-use types but focus on agriculture and livestock	Global: 11 regions	Dynamic model	Base year: 1990; Time step: 15 yrs. Run period: up to 2095	ICLIPS provides AgLU with data on GDP growth by region and the global carbon price. In AgLU, the global carbon price influences the biomass price and production and land-use change. Emissions from land-use change are sent back to the ICLIPS model affecting the climate system. In ICLIPS the carbon price will be adjusted to meet a climate protection strategy.	ICLIPS: Toth *et al.* [189]; AgLU: Sands-Leimbach [60]; Sands-Edmonds [61]

5.3. Research on Integration between Integrated Assessment Models and Earth System Models and Future Effort

Historically, the two modelling groups have looked at the world with different perspectives, communicated in different languages, and used dissimilar modelling strategies. The two of them have traditionally worked with little interaction and their models have been developed independently. However, overlapping areas of focus between the two modelling groups have been extended compared to the past and, lately, more collaboration across groups has occurred [4]. According to van Vuuren *et al.* [7], there are several possible cooperation methods between IAM and ESM communities and the most suitable collaboration type depends on the strength of the interactions and feedbacks, which are to be represented, as well as on the role of uncertainty in simulated processes. Indeed, while the highest level of IA and ES models integration (full coupling) allows for an extensive and coherent treatment of feedback mechanisms, it limits the flexibility in exploring uncertainty as it does not take into account the range of outcomes produced by different IAMs or ESMs (uncertainty space).

The easiest form of integration entails a simple exchange of information between the two groups. For example, the IAM community has recently provided Representative Concentration Pathways (RCPs) to the climate community. Representative Concentration Pathways [190–192] and associated greenhouse gas emissions have been produced by four IAMs (IMAGE, MESSAGE, AIM, GCAM) and are being used by climate models within the World Climate Research Programme’s Fifth Coupled

Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2009). Similarly, the IAM community uses the outcomes of ESMs to develop climate-change impact assessment [7].

An additional step forward is represented by the generation of a set of harmonized land-use scenarios [121] in preparation to the fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). These global scenarios deriving from implementing the RCPs with IAMs, map yearly land-use transitions reconciling historical reconstruction with future projections (1500–2100) at a resolution which is convenient for climate models and ESMs (0.5° × 0.5°). In this way, the IAMs will prescribe time-evolving global vegetation cover taking into account land-use changes. More specifically, starting from the RCPs, a set of gridded land-use change scenarios containing information on urban land, cropland, pastureland, and forestland transitions are produced. The difference between using these scenarios rather than the traditional practice prescribing the geographic distribution of land cover lies in the biogeochemical effects of human-driven land-use change. Also, such an approach assures consistency between land-use changes, concentration pathways, and emissions scenarios used by ESMs. However, while EMSs may include static land-use information, they do not interactively mimic economic and policy driver mechanisms. An attempt to fill this gap has been offered by Bond-Lamberty *et al.* [170], who propose a linking experiment between an IAM (Global Change Assessment Model, GCAM) and an ESM (the Community Earth System model, CESM), thereby making the IAM respond to changes in the ESM climate and biogeochemical cycles. In this way, climate effects from ESM dynamically modulate human decisions on economy and policy within the IAM, allowing for the exploration of the two-way interactions between the earth system processes and the human ones.

6. Conclusions

The design of cost-effective stabilization policies requires taking into account the role of land and its feedbacks with economy, climate, and the environment [173]. The land system involves, simultaneously, a global and a landscape dimension continuously communicating through a series of interactive processes, affecting the economic and climate systems. Therefore, portfolios of mitigation options vary across regions depending on present and future climate, previous greenhouse gases abatement effort, resource endowments and opportunity costs.

Framing such an integrated picture is not trivial. The modelling process has been hindered by the underlying complexity, the lack of data, and the limited research collaboration across modelling groups having diverse (though complementing) expertise. As a result, a big number of exercises have been produced to analyze either biogeochemical, biophysical, or economical elements of the land system, independently. These focus-specific approaches have provided limited room for analyzing the interactions between human and Earth system processes.

Only recently, due to the development of datasets and modelling strategies, the land system has been embedded in climate mitigation analysis, which looks at interactions and feedback mechanisms. Today, IAMs and ESMs integrated frameworks represent the most advanced modelling schemes to deal with the complexity of the land-use and land-cover mechanisms.

While Earth systems are used to understand climate states and the interactions between the Earth's atmosphere, its climate and biogeochemistry, integrated assessment models explore the effects of the human component in the Earth's system (e.g., land-use change). The first puts a limited attention on dynamical and interactive anthropogenic land use, while the second works with low geographical resolution simplifying climate and earth system processes. In other words, IAMs and ESMs are skilled to frame existing feedbacks between, respectively, land use and the economy, and land cover, climate and other physical processes. Both modelling communities acknowledge the need of each other's capability such that relevant collaborations and input exchange between the two have started recently.

Harmonized scenarios on concentrations and emissions, as well as scenarios on global land-cover-change transitions, have been produced and exchanged between the two groups. They will help deepening the understanding of the response of the Earth system to anthropogenic perturbations (e.g., land-use change) leading to climate change.

However, research in this field is very complex and relatively new. More collaboration is required in the years to come to extensively frame feedbacks and interdependences between society, economy and the environment within one comprehensive and robust global-to-local framework. Amongst the areas entailing room for improvement, there are dimensions where a greater effort is required by both modelling frameworks. These areas are reported below:

1. *Time scales*. The temporal dimension of the economic and political system is usually not consistent with the timing of natural cycles in continuous change. Recombining medium time scales (few years) of actual political processes (IAMs) with short time-scales (hours, day) of biophysical processes (ESMs) is not an easy task and generates concerning issues on the integration of spatial biophysical aspects with spatial economic information [7].
2. *Resolution.* ESMs have reported that land-use impacts on climate are more relevant at regional rather than at global scale [3]. Consequently, further effort is needed to reconcile global with regional climate effects of land-use change making use of local assessments, observations and additional inputs and sources. As for IAMs, now that new and global databases have been made available (GTAP-AEZ, FAO-IIASA AEZ, USEPA), gridded or spatially explicit representations have increased. However, current models still operate at a rather low-resolution level (about 1–2 degrees grid intervals), in line with the aggregation of statistics on economic variables [7,193]. The spatial resolution of economic data is constrained by administrative boundaries, which is the level of detail required for economical or policy analysis, not always suitable for environmental variables [13]. Results on land allocation are shown at a coarse level (e.g., country scale) since a more detailed assessment would imply the estimation of data on input usage and output at the spatial unit [6]. This is the case of the MIT-EPPA model [86]. Exceptions for global IAMs are provided by IMAGE, and GTAP-AEZ, which produce analysis at the AEZ level. Higher ESMs resolution, probably comprised between 1 degree and a quarter of a degree (about 100 and 25 km grid intervals, respectively), can be presumably achieved for the next climate model intercomparison exercise (CMIP6) where a specific high-resolution simulations subset (HiResMIP) has been proposed.
3. *Uncertainty*: Great uncertainties still remain relative to the effects of land-use and cover change on the regional climate [121]. This is due to the existence of multi-scale climate dynamics, to the differences in land-use effects on climate across regions, to the interpretation of the land transitions in the land surface models included in the ESMs and differences in the biogeophysical

and, especially, biogeochemical processes included in the LSMs [3]. Advancing convergence on land surface and land-use, land-cover change formulations would reduce these uncertainties within ESMs. Similarly, an improvement is also required in the identification and evaluation of the most important sources of uncertainty permeating IAMs within and across integrated modules. For example, incorporated energy–economic models, not precisely developed for land-use analysis, should confine uncertainty in parameters by using available econometric estimates or by calibrating outcomes to bottom–up approaches. Some aspects of the energy related sector as hydropower can be modelled within ESMs as well [194]. In addition, uncertainty in pests' incidence and diseases in agro-forestry sector would deserve more attention in the representation of vegetation dynamics given their impacts on production, costs, and natural sequestration capacity [166]. Plants can die due to an aggregate of processes such as wind throw, insect attack, disease, extreme temperatures or drought, age-related decline in vigor, and fires, if not considered separately. To account for all the processes mentioned above plant mortality is associated to a bulk constant rate of few percentage points per year, which is clearly an oversimplification.

4. Bioenergy: bioenergy production has become an important and strategic component of the mitigation strategy [195]. Related policy, production and consumption decisions affect land-use and cover changes, and therefore the global-to-regional climate. Given its latest development, there exists a lack of historical data. As a result, current analysis fails to model biomass production competing with both agriculture (food) and forestry (timber) production. Furthermore, they poorly represent competition across different uses of wood, such as wood used for (i) traditional industrial uses; (ii) carbon sequestration; and (iii) biomass production. In addition, within the process of producing the new RCPs, the bioenergy dimension is not consistently handled across IAMs, which use different assumptions to represent its development in time. Further research would be necessary to shed new light on its effect on the economy and its effectiveness as a mitigation strategy.
5. *Forestry.* Including forestry representation into the land-use system is one of the most challenging, though attractive, issues of this field. This explains why several studies have focused on agricultural activities rather than forestry and its mitigation potential (KLUM, ACCELERATES, ELPEN, SALU, WATSIM, IMPACT, CAPRI, GTAP, FARM, GTAPEM, *etc.*). A first issue is the temporal dimension. Growing new forests, increasing forest stock, or accumulating forest-carbon may require more than one decade and therefore long-run analysis [6]. Also, these processes are inherently dynamic. Unfortunately, there is still lack of a description of forest age class evolution and therefore carbon accumulation dynamics. This is true for both economically oriented models with global coverage and some IAMs as well as for ESMs, where usually each plant functional type is treated as a population of plants sharing the same properties, including the age class. More sophisticated models accounting for the age distribution might be considered for future developments of ESMs [196]. Another critical issue relates to the modelling of new land access, namely, forests that, at current conditions, are not economically accessible. Most of the existing models disregard this possibility considering land as a fixed endowment, or restraining the attention of the analysis to managed land. With this modelling structure, it is impossible to track forest-carbon resulting from deforesting new lands,

or carbon sequestration coming from deforestation slowdown, resulting from the introduction of forest sequestration incentives. Similarly, the increase in timber supply derived from new lands brought into production would have no impacts on the economics of the forest sector. A final concern refers to the missing information on forests' non-market value as well as to the "stochastic nature of the real world" [23], aspects practically not modelled in any of the aforementioned analyses.

Acknowledgments

We are grateful to Ramiro Parrado and Enrica De Cian for their valuable suggestions.

Author Contributions

Both authors have contributed differently due to their diverse (but complementary) individual expertise. More specifically, the first author designed the main idea and structure of the paper and developed Sections 2 to 5.2, figures and tables. The second author contributed to Section 5.1. Both authors have researched literature, participated in writing the introduction and conclusion sections (1 and 6) and supervised the final paper content, in addition to formatting the paper according to the *Land* journal requirements.

Conflict of Interest

The authors declare no conflict of interest.

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