ISPRS Int. J. Geo-Inf. **2015**, *4*, 1791-1812; doi:10.3390/ijgi4041791

OPEN ACCESS

ISPRS International Journal of
Geo-Information
ISSN 2220-9964
www.mdpi.com/journal/ijgi

Review

Modeling Historical Land Cover and Land Use: A Review from Contemporary Modeling

Laura Alfonsina Chang-Martínez [1,†], Jean-François Mas [1,†,*], Nuria Torrescano Valle [2,†], Pedro Sergio Urquijo Torres [1,†] and William J. Folan [3,†]

[1] Centro de Investigaciones en Geografía Ambiental, Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de La Huerta, Morelia C.P. 58190, Mexico; E-Mails: changml07@gmail.com (L.A.C.-M.); psurquijo@ciga.unam.mx (P.S.U.T.)

[2] El Colegio de la Frontera Sur Unidad Chetumal, Av. Centenario, Km 5.5 Col. Pacto Obrero, Chetumal C.P. 77014, Mexico; E-Mail: ntorresca@ecosur.mx

[3] Centro de Investigaciones Históricas y Sociales, Universidad Autónoma de Campeche, Av. Agustín Melgar s/n, entre Juan de la Barrera y Calle 20 , Col. Buenavista C.P. 24039, Mexico; E-Mail: wijfolan@gmail.com

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: jfmas@ciga.unam.mx; Tel.: +52(443)-322-3865; Fax: +52(443)-322-3880.

Academic Editor: Wolfgang Kainz

Received: 4 July 2015 / Accepted: 11 September 2015 / Published: 24 September 2015

Abstract: Spatially-explicit land cover land use change (LCLUC) models are becoming increasingly useful tools for historians and archaeologists. Such kinds of models have been developed and used by geographers, ecologists and land managers over the last few decades to carry out prospective scenarios. In this paper, we review historical models to compare them with prospective models, with the assumption that the ample experience gained in the development of models of prospective simulation can benefit the development of models having as their objective the simulation of changes that happened in the past. The review is divided into three sections: in the first section, we explain the functioning of contemporary LCLUC models; in the second section, we analyze historical LCLUC models; in the third section, we compare the former two types of models, and finally, we discuss the contributions to historical LCLUC models of contemporary LCLUC models.

Keywords: cover/land use; modeling; geographic information system

1. Introduction

Human activities, such as logging, agriculture or fire management, cause changes in environmental attributes, including the quality and quantity of available resources, and directly or indirectly have an influence on the processes of desertification, loss of biodiversity, carbon dioxide emissions to the atmosphere and climatic change [1,2]. These changes can either be abrupt or subtle [3–5]. Changes related to agriculture have been constant and with varied intensity since long ago, given that it is known that the first agricultural civilizations appeared nearly 8000 years B.P., and became a factor of land cover/land use change (LCLUC) worthy of attention [6]. Several works have recognized that LCLUC and the intensification of agricultural practices in response to demographic growth can lead to severe change in local or regional environmental conditions [7,8]. Such intensification of agriculture can lead to problems for population persistence [1,3,9–11] and even cause the collapse of civilizations [7,12–18].

The information about past LCLUC aids in understanding present changes and their consequences on the environment. Current research on LCLUC is abundant. LCLUC documents the accelerated loss or degradation of forest cover in many regions of the world, particularly in the past few decades in tropical regions [19]. These studies also recognize that human activity is involved in most of these processes of LCLUC [4,20,21]. Numerous published works based on remote sensing have focused on mapping changes and assessing the rates of LCLUC [22,23]. Other studies go beyond monitoring changes and analyze the processes of LCLUC, identifying its driving factors and modeling the change [24,25]. In particular, spatially-explicit simulation models of LCLUC analyze the relation between changes and the variables affecting them [26,27] in order to obtain maps of potential change (maps of the probability of change) and performing space-time simulations for making land cover prospection maps. Models allow for generating diverse scenarios for testing theories regarding the causes of change. Models also enable the projection into the future of the expected effects of governmental programs aiming at the conservation and utilization of resources. These future projections are based on past evidence (recent past) and allow for adjusting future scenarios [28,29]. For instance, certain models of LCLUC allow for identifying both the processes of change related to forest management and the biophysical and economic forces driving such processes [30]. Other models include decision-making by local communities and the influence of such decisions in land administration [31]. Modeling environmental conditions that determine processes of change is difficult because of the numerous biophysical, socioeconomic and cultural variables involved [7,15,17]. These models apply from the scale of individual parcels to that of large extensions and are used for predicting and explaining both the systems and the effects that human processes have on these systems [27].

Recently published works simulate the LCLUC that took pace in the remote past, which in the present paper we designate as historical LCLUC models, in contrast to simulation models for more recent periods, which we here call contemporary LCLUC models. Some of these publications focus on the assessment of deforestation rates and the emission of greenhouse gases (GHG) [32–35], while other works model the spatial distribution of classes of land cover and land use through time [36,37]. Finally, a group of models focuses on appropriation activities [7,38–40].

Our goal was to review historical LCLUC models in order to compare them with contemporary LCLUC models, with the assumption that the ample experience gained in the development of models of prospective simulation can benefit the development of models having as their objective the simulation of past changes.

The review is divided into three sections: in the first section, we explain the functioning of contemporary LCLUC models; in the second section, we analyze historical LCLUC models; in the third section, we compare the former two types of models, and finally, we discuss the contributions of historical LCLUC models to contemporary LCLUC models.

2. Contemporary LCLUC Models

During the last few decades, an ample variety of models was developed for the analysis and prospective simulation of LCLUC for proposing alternative scenarios, for conducting experiments aimed at understanding changes and for supporting the design of territorial management [41,42].

The National Research Council [27] proposed a classification of the approaches for modeling LCLUC, which was based on theoretical and empirical considerations, the methods employed and the type of application. This classification proposes five categories, ranging from the models based on patterns to the models based on the agents of change, the latter of which are mostly interested in explaining the processes leading to change. A sixth category includes the hybrid approaches (Table 1). Framing models of LCLUC within conceptual approaches allow for a better understanding of their advantages and limitations and for optimizing their application as tools for making prospections and understanding the processes of change.

Approaches focused on patterns are based on data about patterns of LCLUC and tend to use land cover maps obtained by means of satellite images, maps of descriptive variables of the environment and censuses. Generally, these models describe the relation between landscape changes and features based on an analysis of observed past changes in order to make prospective simulations. Approaches based on processes, such as economic models, spatially-disaggregated economic models and models based on agents, are more frequently used in social sciences, being focused on modeling the mechanisms of change.

In order to better explain these different models, we will briefly describe two models located at the extremes of this gradient: (1) a model based on patterns [43]; and (2) another model based on agents [44]. Both models have the objective of simulating the processes of deforestation in two different, but nearby regions located in northern Vietnam. In the first case, Khoi and Murayama [43] classified satellite images in order to elaborate forest cover maps for the years 1993, 2000 and 2007, which allow for mapping deforested areas and for estimating rates of change (by means of a Markov matrix) for the periods 1993–2000 and 2000–2007. Concomitantly, the authors built a database on a geographic information system (GIS) with maps of factors known to be deforestation drivers (*i.e.*, elevation, slope, distance to roads and distance to human settlements). A neural network was trained for establishing a function to relate the spatial distribution of deforestation drivers and deforested areas, which, in turn, allows the authors to elaborate a map of deforestation propensity in which, for example, the more accessible areas (near roads and human settlements) or those with moderate slopes have a high propensity for deforestation. The model simulates deforestation by calculating the expected amount of change for the period of simulation based on rates of change observed during the previous period and simulates the transformation of forest areas more predisposed to deforestation. In the first stage, the authors trained the model using the LCLUC map for 1993–2000 in order to create a prospective map for the year 2007. After that evaluation, observations for the period 2000–2007 were used for simulating changes for the years 2014 and 2021. Therefore, the model is completely based on a statistical analysis of patterns of past change that allow for relating the propensity of change taking into account environmental conditions (*i.e.*, topography, accessibility, suitability for agriculture).

Table 1. Modeling approaches. Modified from National Research Council [27].

Modeling Approaches	**Description**
1. Machine Learning and Statistical Models	Generally automatized, software programs recognize and reproduce the patterns of change. Based on rigorous statistical methods, use observations of changes in order to establish space and time relations between change and drivers.
2. Cellular	Integrates maps of land cover and land use suitability, taking into account the neighborhood effect and information on the amount of change.
3. Spatially-Disaggregated Economic Models	Assess the econometric models in a structural and reduced manner to identify the causal relations having an influence on the spatial equilibrium of land systems.
4. Sector-Based Economic Models	Use models of partial or general structural equilibrium in order to represent the offer and demand of land by economic sectors within the regions based on general economic and commercial activity.
5. Agent-Based Models	Simulate the heterogeneous decisions and actions of actors of change that interact on the land surface, which lead to LCLUC.
6. Hybrid Approach	Includes applications combining different approaches in a single model or modeling frame.

In the case of the agent-based model, Castella *et al.* [44] organized workshops to which peasants were invited to participate in role games in which the player has to manage the landscape in order to sustain his or her virtual families. The decisions made by the players are discussed with participants both during the game, as well as in interviews conducted afterwards, thus allowing the researchers to define different management strategies. A computer simulation was run and presented for discussion at the end of the workshop. The workshop was carried out in localities representing the socio-environmental diversity of the studied region. In a GIS, the model simulates the decisions of actors (e.g., intensify rice cultivation in lowlands or opening new cultivation areas on slopes), taking into account both their characteristics (*i.e.*, size of the household, number of owned animals, extension of owned lands, *etc.*) and the socioeconomic context (*i.e.*, yields, market prices, governmental programs, accessibility, *etc.*). The model spatially simulates the LCLUC related to the decisions made by farmers for the period 1990–2001. The evaluation of the model was based on: (1) the coherence of the amount of simulated change with that obtained from land cover/land use maps for the years 1995, 1998 and 2001; (2) the coherence of the landscape metrics at the levels of settlement and of the district; and (3) a "social" validation consisting of detecting discrepancies between the rules of the model and the opinions of local leaders gathered during validation workshops.

The model of Khoi *et al.* [43] is hence a model based on data, in which the processes of change were not used explicitly, but through an analysis focused on drivers of change. To the contrary, the model of Castella *et al.* [44] is based on expert knowledge gathered during workshops and interviews and is focused on modeling the decisions made by the agents of change. In the following sections, we briefly describe the inputs and the methods for training simulation and validation that are commonly used in contemporary models.

2.1. Inputs

The inputs of pattern-oriented models are commonly maps of land cover/land use for different dates, which frequently were derived from remote sensing data and maps describing potential factors of LCLUC [42].

Typically, such factors are those determining the suitability of the terrain for human activities (*i.e.*, elevation, slope, type of soil), accessibility (*i.e.*, distance to roads or other communication means and distance to human settlements), populational attributes (population density, human activities, social marginality, *etc.*) and areas were certain policies apply (*i.e.*, natural protected areas, areas subject to agricultural foment programs, *etc.*) [45–47]. Models oriented toward agents generally use information about decision-making that leads to LCLUC, which is derived from interviews with key actors of such changes, sometimes being supplemented by cartography and censuses.

2.2. Training or Calibration of the Model

Training or calibration of the model consists of establishing the parameters that control the behavior of the model. Models oriented toward patterns, which are based on trends observed in the past, usually obtain such information by the comparison of two maps of LCLU from previous dates [42]. Such comparisons allow for estimating annual rates of change during the analyzed period, frequently by means of a Markov matrix. A Markov matrix expresses the proportion of a given land cover that would be transformed to another land cover type, assuming that the observed trends will remain the same (stationary process), thus allowing their projection to the future [48]. Furthermore, a statistical analysis allows for relating factors of change (such as slope or accessibility) to the observed changes. That relation is established by different methods, such as regression models, weights of evidence [49] and artificial intelligence [50], among others. The product is a map containing values indicating the propensity for change. Numerous variations exist, for example in the amount of change that can be estimated by means of an external model [51], while the map of potential change can be obtained through methods enabling the incorporation of expert knowledge in order to depart from modeling strictly reproducing the patterns of change observed during the previous period [52,53].

In agent-oriented models, calibration consists of determining the rules of the behavior of the agents, which is generally achieved by means of interviews informing about the criteria used by the actors of change when making a decision that will affect land use and land cover [44].

2.3. Simulation

In pattern-oriented models, simulation is achieved by modifying the input map so that it displays LCLUC. The model calculates the amount of change corresponding to the time period used in the simulation and applies changes to areas according to their value of potential for change. Some models use cellular automatons in order to reproduce the spatial patterns of LCLUC, while controlling the size and shape of the simulated change patches [51]. Because agent-oriented models are focused on simulating processes of change, they are sometimes implemented in virtual landscapes. However, agent-oriented models are commonly coupled with GIS containing the database of real landscapes to simulate more realistic patterns of change [44].

2.4. Model Assessment

Models oriented toward patterns of change are usually assessed based on the evaluation of the spatial coincidence between a real, observed map and a simulated map. To that end, land cover/land use maps of a minimum of three different times are commonly used, calibrating the model for the first two dates in order to obtain a simulated map for the third date. The model is assessed by estimation of the degree of similarity between the simulated and the real maps. Because the majority of the landscape does not display changes, such similarity can be very high, even for mediocre models [54], so it is recommended to focus the evaluation on changes (real *v.s.* simulated changes). The evaluation is generally centered on assessing spatial coincidence between simulated and real changes by means of several indexes, such as the Kappa index [55], the index of fuzzy coincidence [56] and other indexes of coincidence that can be used at several resolutions, thus allowing for a certain tolerance regarding coincidence [44,57]. Some authors propose the use of other indexes, for example indexes of landscape fragmentation [58]. The evaluation can either focus on maps of propensity to change by means of an analysis of the receptive operational characteristic (ROC) or be centered on the differences in the potential for change [47]. Agent-oriented models having prospective LCLUC maps as their output can be assessed by the same methods used for maps resulting from process-oriented models. However, because different processes can lead to similar landscapes and because the main goal of agent-oriented models is modeling the processes of change, their evaluation focuses on the agent's rules for decision-making [44]. It is worth noting that prospective models exhibit often a poor predictive power [59], due to the non-stationarity of LCLUC processes and to the fact that the factors of change used in the model do not control the patterns of changes strictly.

3. Historical LCLUC Models

Hayashida [60] identifies three main motivations for the historical modeling of LCLUC: (1) a growing interest for the processes of historical landscape change; (2) the recognition of human beings as a part of the history of the landscape; and (3) the advent of restoration ecology aiming at restoring degraded ecosystems based on historical references. Other researchers focus on changes in those properties of the land surface that are associated with LCLUC and alter the climate through the modulation of exchanges of energy and gases with the atmosphere. These authors report that carbon dioxide and methane emissions due to human activities during time periods of hundreds of years have a strong influence on present problems, such as climatic change [61,62]. According to Williams' historical review [63], deforestation is the most important transformer of land cover due to the extension of the geographic surface it has modified during thousands of years. Recent works show that the inhabitants of Europe during the late Neolithic period, or New Stone Age (4500–4000 years B.C.), as well as the civilizations of North America and other parts of the world were already conformed as sedentary societies with a diversified economy and had a significant impact on native vegetation. It is estimated that the world's extension of pre-agriculture forests was of 61.51 million km^2, of which 15.51 million km^2 were lost prior to about 1500 A.D. The historical LCLUC models are relatively scarce and were mostly developed during the past two decades in several parts of the world, mainly in China, the USA, Europe and South America (Figure 1 [7,34,37,39,62–70]). Historical models of change have distinct disciplinary origins and use different space-time scales. As seen in Figure 2, some studies cover study areas of a few hundreds of km^2, while others have continental or global scales; likewise, some studies have a span of a few hundreds of years, while others comprise tens of thousands of years.

We identified three large groups of models according to their modalities. The first group includes pattern-oriented models having as their goal the evaluation of atmospheric alterations due to LCLUC and their possible effect on climatic change and global warming. These models are based on the elaboration of a series of maps at the regional or global scale representing the patterns of greenhouse effect gas (GHG) emissions. Emissions of GHG are estimated based on maps of populational density and vegetation, which allow for evaluating the probable extension of deforestation and of emitted GHG [61,71–75].

The second group, with less numerous contributions, includes agent-oriented models attempting to understand the socio-environmental processes and their relation to LCLUC [7,15,39,40,64,76,77]. In general terms, the study areas of these models are small, ranging from a couple to hundreds of square kilometers. Most of these models use archaeological inputs and have as their goals either the reconstruction of the behavior of past civilizations or attempting to find explanations for their sudden collapse [18].

Finally, the third group of contributions is based on a hybrid modeling allowing for obtaining patterns of change taking into account social and biophysical variables combined with historical, archaeological, archaeozoological, archaeobotanical or paleoecological records, among others. Modeling is focused on patterns of landscape change, emphasizing the realistic simulation of the spatial distribution of the elements of the landscape [37,65,78]. In some cases, these models simulate the interaction between the processes of change and ecosystem degradation processes, such as soil erosion [79]. Some similarities

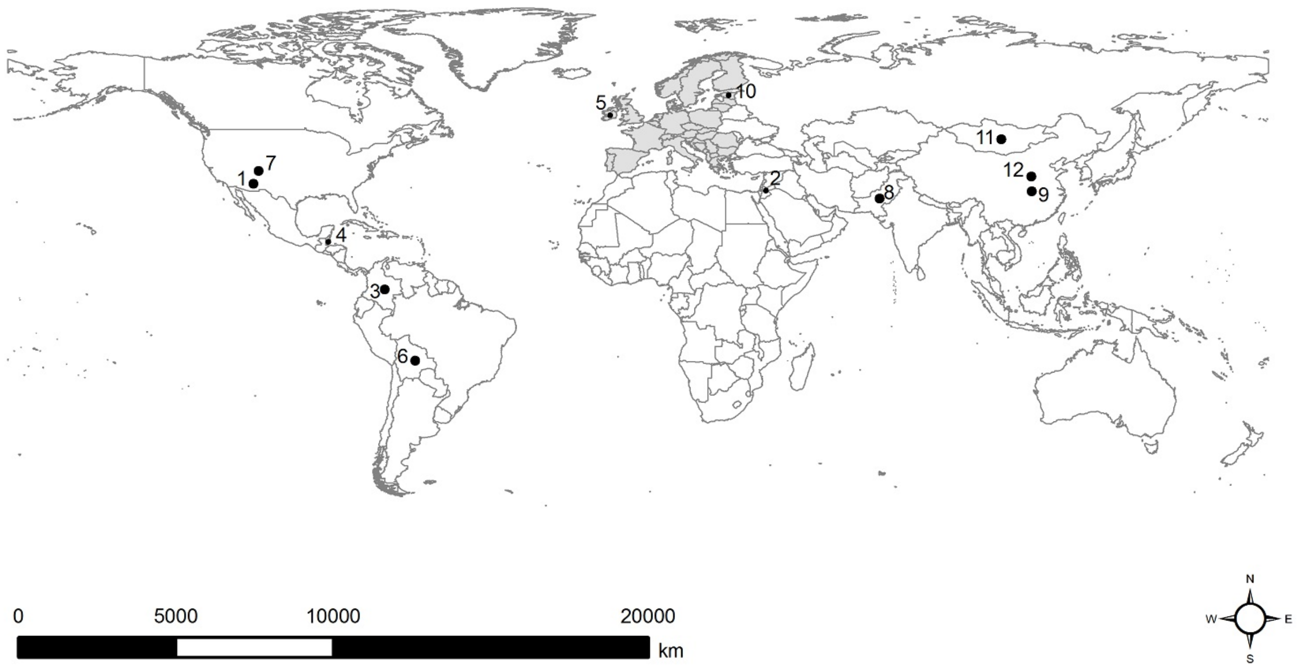

Figure 1. Spatial distribution of the reviewed historical LCLUC models. References: 1. [7]; 2. [66]; 3. [65]; 4.[67]; 5.[68]; 6.[39]; 7.[64]; 8.[34]; 9.[62]; 10. [69]; 11.[70]; 12. [37]; [63] The last study includes all of Europe (shown as the shaded area in the map).

between models within each group became evident (Figure 2 [7,32–35,37,39,62–67,69–72,75,80–83]). Models made for estimating GHG emissions mostly use small scales, given that such estimates do not require much detail and are more useful when they provide global information or are used as inputs for climatic models. The time periods covered by these models depends on the database used as a reference of LCLUC and are generally of hundreds or thousands of years (e.g., 6000 years B.P. to present).

In comparison, agent-based models are limited to the use of large scales, given that they simulate the behavior of individuals or a group of individuals. Due to the complexity of the systems that are to be modeled (involving social processes), these models predominantly focus on short periods of time. The majority of the agent-based models are centered on modeling changes associated with early civilizations for which sufficient archaeological records are available for elaborating the model.

The hybrid models are scarce and can be quite flexible regarding their space and time scales, because they represent a compromise between pattern and process-focused models.

3.1. Objectives

We found a diversity of objectives for historical modeling: estimation of GHG emissions derived from the development of agricultural areas [32,34,84]; knowing the agricultural production potential of areas in prehistoric times [7] and or representing socioeconomic processes during the onset of agriculture; analyzing the relation between land management and the processes of soil erosion and deposition [79]; reconstructing human activities, both at small and large scales, such as sedentarism, herding and hunting-gathering [17,64,70,76,77]; and modeling both the origins of sedentary life and of the first urban settlements, as the associated environmental impacts [40].

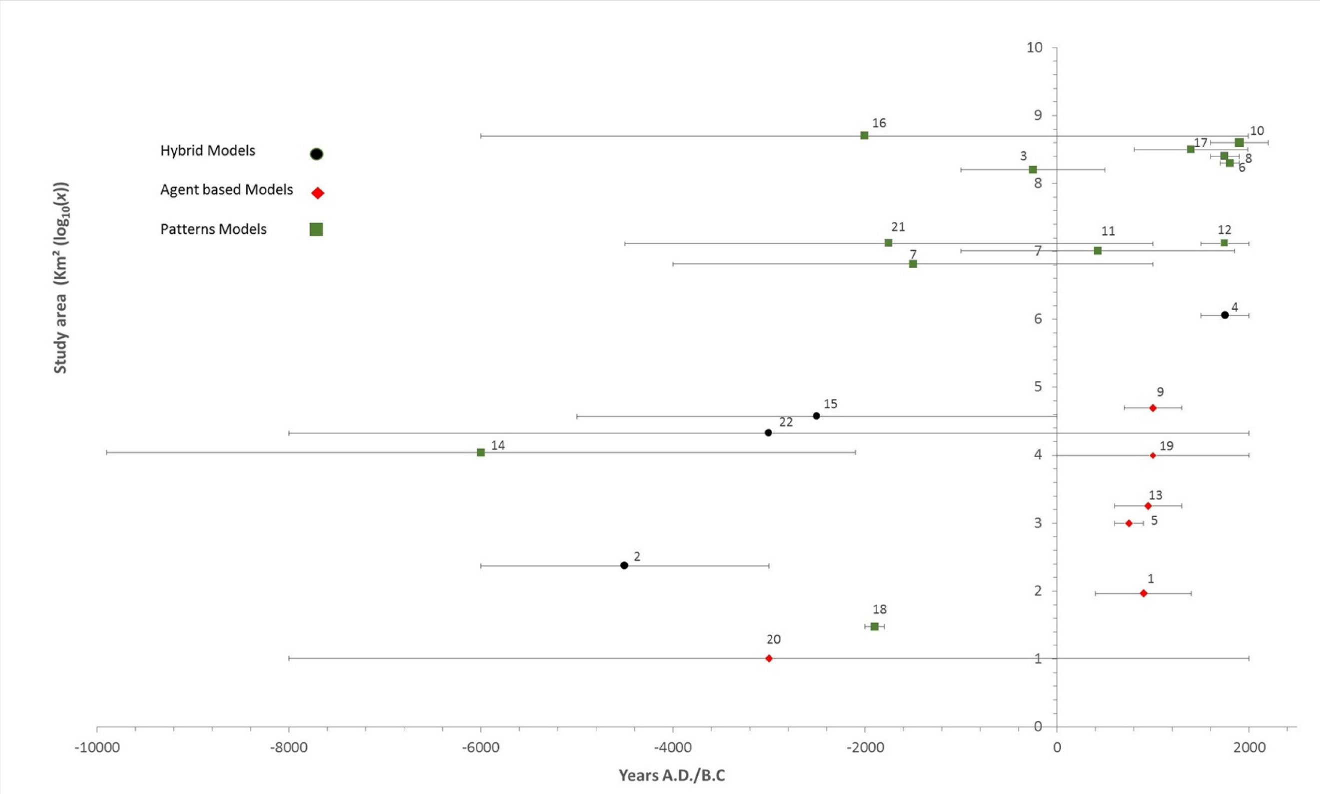

Figure 2. Spatial and temporal scales of the reviewed historical LCLUC models. The three groups of models tend to be associated with different scales. References: 1. [7]; 2. [66]; 3. [75]; 4. [65]; 5. [67]; 6. [71]; 7. [80]; 8. [72]; 9. [39]; 10.[81]; 11. [33]; 12. [35]; 13. [64]; 14. [34]; 15.[62]; 16. [82]; 17. [32]; 18.[69]; 19. [70]; 20. [83]; 21. [63]; 22.[37].

3.2. Inputs

The inputs of historical models of LCLUC contain a limited amount of information compared to those used by contemporary models, thus forcing modelers to recur to different disciplines, such as archaeology, paleoecology, palynology, paleontology, history and anthropology, in order to obtain the needed information. For example, palynology can be used for evaluating agricultural areas through the analysis of fossil pollen records [69] and the paleoecological and paleoenvironmental records that enable knowing which animals and plants were domesticated in the settled territories [7]. As a consequence, historical modeling studies are mostly interdisciplinary. Obtaining as much information as possible about past records allows establishing settlement patterns, possible land and resource uses and cultural practices, thus determining probable areas of LCLUC. In general, the main input is the archaeological record for generating the rules or norms defining the processes and patterns of the agricultural consumption of the population, as well as the interaction between them and the physical environment [7,37,40]. Archeology can also provide information about past forms of water management and social norms [77]. Another possible input is the historical record and the historical literature containing dependable information regarding past events, although the coverage of the past of these inputs is limited in time [65]. Certain studies include attributes of the population dynamics, such as demographic pressure, competition for resources and carrying capacity obtained from historical records [85].

Because geological processes require thousands of years to drastically change, it is possible to use present geological and topographical information [14]. Other present time inputs that have been used are satellite images, orthophotos, soil maps and unconsolidated sediment maps and geomorphologic maps [34,80]. Occasionally, in studies of recent time periods (a few hundreds of years) or when pollen records do not indicate plant associations different from the present, it is possible to use present vegetation type maps [7,66,86].

Databases with information about past LCLUC derived from modeling are also available and can be incorporated into simulation models [32,72,74]. One of these databases is the History Database of the Global Environment (HYDE) [71] covering the past 300 years [33,35,82]. HYDE was developed in order to test and validate a global environmental model and is based on historical population estimates and the distribution of croplands. Populational data were obtained from the Atlas of World Population History [87]. Data in HYDE are presented at a five-minute resolution and include 14 vegetation types. The database divides the world into 19 groups, each one with several subregions [71].

A second source is the Anthropogenic Land Cover Change database covering the time period from 800–1992 A.D., accompanied by high-resolution maps from the Center for Sustainability and the Global Environment (SAGE) compiled by Pongratz *et al.* [32]. According to these authors [32], the database is a tool for studies of global change emphasizing estimates of GHG emission; also including demographic and plant cover estimates. It combines satellite information and specific algorithms rendering multi-temporal world maps for the past 300 years [34,81].

Finally, a research group focusing on the relationships between soil, vegetation and atmosphere produced a database from a model that simulates prehistoric and pre-industrial LCLUC [33]. This database contains maps of agriculture, herding, climate and soil properties in Europe at a continental scale, covering the time period from 1000 B.C.–1850 A.D.

Other models of LCLUC occasionally use as input the outputs of other models explaining the behavior of populations. For example, Patterson *et al.* [85] use the model of Aoki *et al.* [88] that simulates the interactions in the Neolithic between populations of hunter gatherers and farmers.

3.3. Training and Simulation

Modelers of past LCLUC apply several methodologies. The models that are focused on making estimates of worldwide croplands relate population density and the expected land use derived from the activities of the population. In the cases of HYDE and ALCC, the estimation assumes a linear relation between population and the surface area of croplands. However, Kaplan *et al.* [33] use a non-linear relation between populations and cropped areas, adopt parameters of technological development and intensification (Industrial Revolution), include wood extraction and account for fallow periods and shifting agriculture. Although the three datasets used the same population estimates as a proxy, they exhibit different reconstruction results due to differences in the methodology. Yan *et al.* [89] pin point that uncertainties of the reconstructions constitute an issue that needs to be addressed.

In turn, these models can be used as input for models estimating emission to the atmosphere and sequestration of GHG [35,68,83,90,91]. Some models simulate carbon flux between natural vegetation, crops, soil and atmosphere, taking into account the changes in land cover and time series, temperature, precipitation and atmospheric concentration of CO_2 [33,63,78,82]. These models use present data. For instance, Kaplan *et al.* [35] use the soil map of the Harmonized World Soil Database, and Olofsson and Kickler (2007) [33] use vegetation indexes derived from satellite images in order to estimate the net primary production of different types of vegetation.

Simulations focused on historical LCLUC patterns use statistical methods for making simulations more robust; for example, Kolmogorov's chains or goodness of fit tests are used for calibrating input maps [37,65,79,92]. Examples are the three sub-models used for the distribution of agriculture in the Yiluo Valley in northern China: (1) the land use need sub-model estimating the total area of cropland needed for supplying the human population of the region for the different time periods modeled; (2) the residential area sub-model that generates a map of the potential distribution of the human population based on the analysis and distribution of archaeological sites in relation to environmental variables by means of the Kolmogorov goodness of fit test; and (3) the land use allocation sub-model that distributes the surface of croplands determined by Sub-model 1 around archaeological sites taking into account the map of potential distribution from Sub-model 2. These simulations are made for different dates at 1000-year intervals beginning in 8000 B.P. and until the present, thus accounting for the antiquity of the archaeological sites and the estimates of population [37]. Camacho *et al.* [93] adopt a retrospective approach for elaborating maps of the distribution of irrigated and rainfed agriculture in the years 1572, 1752 and 1855–1861, based on a land use map for 1957 and censual data of the surface of irrigated and rainfed agriculture. For that purpose, the authors elaborated suitability maps using multi-criteria analysis based on invariable through time criteria, such as slope, elevation and distance to irrigation channels and settlements. Each criterion is weighted based on the results of a coincidence analysis of criteria and uses from the 1957 land use map. Coincidence was evaluated by means of the Pearson's correlation coefficient and Cramer's V correlation.

The agent-based models use local scales, so that they can be focused on the process of LCLUC. The interactions between the agents and the landscape (LCLUC) and between agents (e.g., reproduction and commercial exchange) are modeled. If the model is spatially explicit, it is possible to map environmental changes. The obtained information is largely qualitative; however, it is possible to generate descriptive statistics data [15,39,94]. For example, the model of agents of Axtell *et al.* [7] recreates demographic growth and the collapse of a settlement of the Anasazi civilization in Long House Valley during the time period from 800 A.D.–1300 A.D. by means of multiagent decision-making rules. The model simulates activities along the life cycle of virtual households (agents), such as productive activities, consumption and social interactions, like marriage and trade. The model's functioning is based on rules and parameters, the rules prescribing the creation and location of new households, *i.e.*, a new household is created when the daughter reaches 15 years of age, and its location is defined by suitability for agriculture and the proximity to sources of water. Some of the parameters used include the nutritional requirements of individuals and their life expectancies. These rules and parameters were obtained from archaeological and paleoenvironmental records. The model takes into account the climatic variability observed in dendroclimatic, pollen, geomorphological and archaeological records. Finally, the model simulates the evolution of the landscape (*i.e.*, distribution patterns of settlements and croplands).

Regarding hybrid models, these contain both qualitative and quantitative information allowing for mediating between agent-based modeling (processes) and pattern-based modeling. For example, the model landform-evolution (CYBEROSION) simulates the interactions between humans, domestic and wild animals, vegetation and erosion in prehistoric communities. The model allows for evaluating the vulnerability of the landscape to anthropic processes, such as, for example the increment of erosion rates at higher anthropic pressure. Agents are used for interactions between basic processes, such as food acquisition [95]. Another example of a hybrid model is that of Poska *et al.* [69], who model the changes between four categories of land cover/land use by means of Markov chains and fossil pollen records from between 600 B.C. and 1940 B.C. The authors deduce the percentage of cover corresponding to certain amounts of pollen by a comparison with modern analogs.

3.4. Validation

The evaluation of spatially-explicit simulation models allows for knowing both the degree of confidence of the obtained maps and the performance of the model. The validation of contemporary models is mainly based on the spatial coincidence between the map of the distribution of the elements from the real landscape and the simulated map. Obviously, this approach is impossible to use for simulations of the past, given that such a distribution is insufficiently known. Maybe for that reason, models for the historical simulation of LCLUC are, in general, not subjected to validation tests.

Some ways of evaluating historical models were focused on comparing the distribution of the actual archaeological sites with the predicted occupation [7,94]. For that purpose, occupation sites are modeled using as input a part of the location of archaeological sites, the remaining such sites being compared to the sites predicted by the model, thus allowing for assessing if the model underestimates or overestimates the amount of sites [76]. In such cases, the pattern of change is not evaluated. Another possibility is comparing past areas of change in relation to present ones [65]. For instance, Yu *et al.* [37] model the expansion of croplands from 8000 B.P. until the present and measure the coincidence between the last simulated map and a present map by means of the Kappa index. Poska *et al.* [69] compared proportions of land cover derived from fossil pollen records, historical maps and simulated maps. In the case of models in which GHG emissions are estimated, it is also common to extend the simulation until the present time and the generation of scenarios with and without anthropic disturbances. This form of validation can only be applied to models that differentiate between natural cycles and human actions [83].

Model assessment is important to evaluate the quality of the information obtained from the model and should be focused on the objective of model. For example, if the model aims at reconstructing a landscape, the spatial coincidence between simulated and true elements is important. However, if the model aims at evaluating landscape transformation or GHG emission, the evaluation of the simulated proportion of different land covers is sufficient. Ideally, data used for model calibration and assessment are independent.

4. Discussion

The objectives of contemporary models are to improve the understanding of the interactions between LCLUC and a diversity of environmental or social processes, to make prospections under different scenarios and to support decision-making processes. Likewise, the historical models of LCLUC are an aid in the understanding of the configuration of historical landscapes and in the testing of hypotheses regarding past changes. In particular, historical models are useful for recovering degraded ecosystems by using the conditions derived from historical references [27,60]. Therefore, the goal of both the contemporary and the historical models is finding more sustainable systems of land use.

There is an ample range of approaches, software and methods for contemporary models. As shown in our review, historical models are few in comparison to contemporary models; however, the former use an ample diversity of approaches and methods. Such diversity may be confusing when trying to choose the appropriate approach and method for the desired goals and the available inputs. In the case of contemporary models, reviews and methodological assessments exist that provide guidelines for choosing the models [27,42,47]. For instance, pattern-based models are more appropriate for problem identification, because, despite lacking structural details about the process, they are needed for evaluating the effects of change, are easy to apply and can provide valuable descriptions, projections of patterns and trends. Approaches based on economic and structural agents provide the means for exploring the interactions within the human-environment system, as well as for assessing the consequences of policies and decisions made regarding land uses and their probable effects [27].

Contemporary models can contribute to historical models, mostly in terms of methodology; nevertheless, certain considerations must be taken into account regarding the particularities of the inputs available for historical models. Inputs are radically different for both types of models: while contemporary models depend on land use maps of the complete study area, censual and demographic data and interviews, the inputs available for historical models are limited. Historical models mainly use archaeological, anthropological and paleoenvironmental inputs, which are exposed to subjective and sometimes erred interpretations, such as the estimation of the potential population density or of the distribution of past civilizations [96,97].

Due to its nature, the historical record does not provide detailed temporal and spatial information; for example, the pollen record provides no precise temporal information, because usually only some strata are dated, the remaining dates being inferred by interpolation [69]. Likewise, pollen data allow for estimating the proportions of plant covers, but it is difficult to establish the represented area and the spatial distribution of plant communities. Similar limitations are present in the archaeological records, dating being subject to the availability of artifacts, such as pottery and pigments. Furthermore, parts of the record are frequently lost for a long time, either because of looting, deliberate destruction of cultural features, erosion or deposition [79]. Records about the past are generally scarce, which is further relevant when attempting to use part of the inputs for training the model and another part for validating it [65,76]. Another limitation for modeling is that socio-environmental processes can change in short periods of time [98,99]. According to our review, most historical models are focused on the reconstruction of past landscapes at certain date, but do not dynamically simulate the processes of change through time. There is a trend for contemporary models to simulate LCLUC processes in a more realistic way, for instance by means of simulating vegetation succession and agricultural cycles, thus enabling the simulation of environmental processes, such as soil erosion, fire, landslides, forest degradation or desertification. Contemporary models applied to cases from the past allow for testing hypothesis about the conditions that may have favored processes of environmental degradation. LCLUC models may acquire the behavior of a complex system, as in dynamic cultural interactions and climatic changes [100–103].

5. Conclusions

(1) We identified three large groups of historical models of LCLUC: pattern-based models, agent-based models and hybrid models.

(2) The historical LCLUC models could benefit from the vast experience accumulated by contemporary modeling of LCLUC; however, the inputs required for historical modeling are drastically different and have limitations. Because of the scarceness and characteristics of the inputs used, historical models cannot be totally based on data (data driven), but must rather be largely based either on expert knowledge or on hybrid approaches.

(3) Most models of past LCLUC aim at reconstructing the landscape for a given date rather than at making simulations between dates. This means that historical models are not dynamic through time. Recently, historical simulation has been oriented towards more realistic models of the processes of LCLUC, which allows for better understanding problems, such as environmental deterioration. It is likely that some historical models of LCLUC will adopt that same trend.

(4) Depending on the objective of modeling and inputs, an appropriate modeling approach should be chosen. Agent-based models are preferred when modeling decision-making; pattern-based models are suggested when models aim at reconstructing past landscapes or simulating LCLUC changes.

(5) The quantity and quality of inputs directly determines the performance of the model and limits the possibilities for its evaluation. Awareness must be kept about the fact that modeling is an exercise of the simplification of reality and that results must be interpreted cautiously. However, model assessment, which is a common practice in contemporary models, should be adopted in past modeling and adapted to the modeling objectives.

Historical models of LCLUC spatially and temporally represent human use of land and land management practices (agriculture, forestry, animal husbandry), thus providing new approaches for archaeological investigation that allow for the simulation of past civilizations by interrelating the variables of a dynamic complex system or by simulating the interaction of different land management practices. Additionally, historical models of LCLUC aid in reconstructing the history of the environment (environmental history and historical ecology), providing information about the landscape (ecology and geography), while facilitating the spatial referencing of historical studies. Historical simulation is thus a new tool for the spatial analysis of historical processes, for both social and environmental sciences.

Acknowledgments

This research has been supported by the project "Puede la modelación espacial ayudarnos a entender los procesos de cambio de cobertura/uso del suelo y de degradación ambiental" (SEP-CONACYT 178816). We acknowledge Maria del Rosario Domínguez Carrasco, Sergio Zárate and three anonymous reviewers for their very useful and constructive comments on a preliminary version of the manuscript.

The first author acknowledges the Consejo Nacional de Ciencia y Tecnología for grant number 239247.

Author Contributions

Laura Alfonsina Chang-Martínez and Jean-François Mas carried out the process of gathering and evaluating the information and prepared a preliminary version of the manuscript. All authors discussed the results and commented on the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Lambin, E.F.; Geist, H.J.; Lepers, E. Dynamics of land-use and land-cover change in tropical regions. *Annu. Rev. Environ. Res.* **2003**, *28*, 205–241.
2. Galicia, L.; Romero, A.G.; Mendoza, L.G.; Ramírez, M.I. Cambio de uso del suelo y degradación ambiental. *Ciencia* **2007**, *58*, 50–59.
3. Geist, H.J.; Lambin, E.F. *What Drives Tropical Deforestation? A Meta-Analysis of Proximate and Underlying Causes of Deforestation Based on Subnational Case Study Evidence*; Ciaco Printshop (University of Louvain): Rue de Rodeuhaie, Belgium, 2001.
4. Lambin, E.F.; Turner, B.; Geist, H.J.; Agbola, S.B.; Angelsen, A.; Bruce, J.W.; Coomes, O.T.; Dirzo, R.; Fisher, G.; Folke, C.; *et al.* The causes of land-use and land-cover change: Moving beyond the myths. *Glob. Environ. Chang.* **2001**, *11*, 261–269.
5. Houet, T.; Loveland, T.R.; Hubert-Moy, L.; Gaucherel, C.; Napton, D.; Barnes, C.A.; Sayler, K. Exploring subtle land use and land cover changes: A framework for future landscape srudies. *Landsc. Ecol.* **2010**, *25*, 249–266.
6. Redman, C.L. *Los Orígenes de la Civilización. Desde Los Primeros Agricultores hasta la Sociedad Urbana en el Próximo Oriente*; Editorial Crítica: Barcelona, Spain, 1990.
7. Axtell, R.L.; Epstein, J.M.; Dean, J.S.; Gumerman, G.J.; Swedlund, A.C.; Harburger, J.; Chakravarty, S.; Hammond, R.; Parker, J.; Parker, M. Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 7275–7279.

8. Bithell, M.; Brasington, J. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environ. Model. Softw.* **2009**, *24*, 173–190.
9. Diamond, J.M. *Collapse: How Societies Choose to Fail or Succeed*; Penguin Books: London, UK, 2005.
10. Beach, T.; Dunning, N.; Luzzadder-Beach, S.; Cook, D.; Lohse, J. Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. *Catena* **2006**, *65*, 166–178.
11. Denevan, W.M. Una perspectiva histórica sobre el descubrimiento del Campos Elevados (Camellones) prehipánicos. In *Agricultura Ancestral Camellones y Albarradas. Contexto Social, usos y retos del Pasado y del Presente.*; Valdez, F., Ed.; IFEA: Ecuador, Brazil, 2006; pp. 17–24.
12. Culbert, T.P. *The Classic Maya Collapse*; University of New Mexico press: Albuquerque, NM, USA, 1973.
13. Yoffe, N.; Cowgill, G.L. *The Collapse of Ancient States and Civilizations*; University of Arizona Press: Tucson, AZ, USA, 1991.
14. Haug, G.H.; Günther, D.; Peterson, L.C.; Sigman, D.M.; Hughen, K.A.; Aeschlimann, B. Climate and the collapse of Maya civilization. *Science* **2003**, *299*, 1731–1735.
15. Kohler, T.A.; Gumerman, G.J.; Reynolds, R.G. Simulating ancient societies. Computer modeling is helping unravel the archaeological mysteries of the American Southwest. *Sci. Am. INC* **2005**, *293*, 76–84.
16. Springs, K.D.; Litt, M. Civilization, transformation and collapse. *J. World Anthropol. Occas. Pap.* **2007**, *3*, 97–112.
17. Kohler, T.A.; Cockburn, D.; Hooper, P.L.; Bocinsky, R.K.; Kobti, Z. The coevolution of group size and leadership: An agent-based public goods model for prehispanic pueblo Societies. *Adv. Complex Sys.* **2012**, *15*, 1–29.
18. Turner, B. L., II; Sabloff, J.A. Classic period collapse of the Central Maya Lowlands: insights about human-environment relationships for sustainability. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 13908–13914.
19. Duran-Medina, E.; Mas, J.; Velázquez, A. Cambios en las coberturas de vegetación y usos de suelo en regiones con manejo forestal comunitario y áreas naturales protegidas de México. In *Los Bosques Comunitarios de México. Manejo Sustentable de los Paisajes Forestales*; Bray, D., Merino, L., Barry, D., Eds.; Instituto de Geografía-UNAM: Coyoacán, Mexico, 2007; pp. 267–299.
20. Gerber, P.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. *Enfrentando el Cambio climático a través de la Ganadería—Una Evaluación Global de las Emisiones y Oportunidades de Mitigación.*; Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO): Roma, Italy, 2013.
21. OECD/FAO. *OCDE-FAO Perspectivas Agrícolas 2014-2023*; OECD Publishing: Paris, France, 2014.
22. Alves, D.S.; Skole, D.L. Characterizing land cover dynamics using multi-temporal imagery. *Int. J. Remote Sens.* **1996**, *17*, 835–839.

23. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; *et al.* High-resolution global maps of 21st-century forest cover change. *Science* **2013**, *342*, 850–853.
24. Turner, B.L.; Geoghegan, J.; Foster, D.R. *Integrated Land-Change Science and Tropical Deforestation in the Southern Yucatán. Final Frontiers*; Oxford University Press: Oxford, UK, 2004.
25. Sanchez, I.B.; Alonso, C.L. *Deforestation research progress*; Nova Science: New York, NY, USA, 2008.
26. Mas, J.F.; Sandoval, A.F. Modelación de los cambios de coberturas/uso de suelo en una región tropical de México. *Geotrópico* **2011**, *5*, 1–24.
27. National Research Council. *Advancing Land Change Modeling: Opportunities and Research Requirements*; The National Academies Press: Washington, DC, USA, 2014.
28. Soares-Filho, B.; Moutinho, P.; Nepstad, D.; Anderson, A.; Rodrigues, H.; Garcia, R.; Dietzsch, L.; Merry, F.; Bowman, M.; Hissa, L.; *et al.* Role of Brazilian Amazon protected areas in climate change mitigation. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 10821–10826.
29. Wyman, M.S.; Stein, T.V. Modeling social and land-use/land-cover change data to assess drivers of smallholder deforestation in Belize. *App. Geogr.* **2010**, *20*, 329–342.
30. Chowdhury, R.R. Driving forces of tropical deforestation: The role of remote dending and spatial models. *J. Trop. Goegr.* **2006**, *27*, 82–101.
31. Geoghegan, J.; Villar, S.C.; Klepeis, O.; Mendoza, P.; Ogneva, M.; Himmelberger, Y.; Chowdhury, R.; Turner, B. L., II; Vance, C. Modeling tropical deforestation in the southern Yucatán peninsular region: Comparing survey and satellite data. *Agric. Ecosyst. Environ.* **2001**, *85*, 25–46.
32. Pongratz, J.; Reick, C.; Raddatz, T.; Claussen, M. A reconstruction of global agricultural areas and land cover for the last millennium. *Glob. Biogeochem. Cycl.* **2008**, *22*, doi:10.1029/2007GB003153.
33. Kaplan, J.O.; Krumhardt, K.M.; Zimmermann, N. The prehistoric and preindustrial deforestation of Europe. *Quat. Sci. Rev.* **2009**, *28*, 3016–3034.
34. Lemmen, C. World distribution of land cover changes during Pre- and Protohistoric Times and estimation of induced carbon releases. *Géomorphol. Relief Process. Environ.* **2010**, *4*, 303–312.
35. Kaplan, J.O.; Krumhardt, K.M.; Zimmermann, N.E. The effects of land use and climate change on the carbon cycle of Europe over the past 500 years. *Glob. Chang. Biol.* **2012**, *18*, 902–914.
36. Paegelow, M.; Camacho Olmedo, M. *Modelling Environmental Dynamics*. Springer: Berlin, Germany, 2008.
37. Yu, Y.; Guo, Z.; Wu, H.; Finke, P.A. Reconstructing prehistoric land use change from archeological data: Validation and application of a new model in Yiluo valley, northern China. *Agric. Ecosyst. Environ.* **2012**, *156*, 99–107.
38. Parker, D.C.; Bergher, T.; Manson, S.M. Agent-based models of land-use and land-cover change. In Proceddings of an International Workshop, Irvine, CA, USA, 4–7 October 2011; pp. 4–7.

39. Griffin, A.F.; Stanish, C. *An Agent-based Model of Prehistoric Settlement Patterns and Political Consolidation in the Lake Titicaca Basin of Peru and Bolivia*; eSholarship: Oakland, CA, USA, 2007.
40. Macmillan, W.; Huang, H.Q. An agent-based simulation model of a primitive agricultural society. *Geoforum* **2008**, *39*, 643–658.
41. Veldkamp, A.; Verburg, P.H. Modelling land use change and environmental impact. *J. Environ. Manage.* **2004**, *72*, 1–3.
42. Mas, J.F.; Kolb, M.; Paegelow, M.; Camacho Olmedo, M.T.; Houet, T. Inductive pattern-based land use/cover change models: A comparison of four software packages. *Environ. Model. Softw.* **2014**, *51*, 94–111.
43. Khoi, D.D.; Murayama, Y. Forecasting areas vulnerable to forest conversion in the Tam Dao National Park region, Vietnam. *Remote Sens.* **2010**, *2*, 1249–1272.
44. Castella, J.C.; Trung, T.N.; Boissau, S. Participatory simulation of land-use changes in the Northern Mountains of Vietnam: The combined use of an agent-based model, a role-playing game, and a geographic information system. *Environ. Model. Softw.* **2005**, *10*, 1–27.
45. Soares-Filho, B.S.; Cerqueira, G.C.; Pennachin, C.L. DINAMICA—A stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecol. Model.* **2002**, *154*, 217–235.
46. Verburg, P.H.; de Groot, W.T.; Veldkamp, A.J. Methodology for multi-scale land-use change modelling: concepts and challenges. In *Global Environmental Change and Land Use*; Dolman, A.J., Verhagen, A., Rovers, C.A., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2003; pp. 17–51.
47. Pérez-Vega, A.; Mas, J.F.; Ligmann-Zielinska, A. Comparing two approaches to land use/cover change modeling and their implications for the assessment of biodiversity loss in a deciduous tropical forest. *Environ. Model. Softw.* **2012**, *29*, 11–23.
48. Takada, T.; Miyamoto, A.; Hasegawa, S.F. Derivation of a yearly transition probability matrix for land-use dynamics and its applications. *Landsc. Ecol.* **2009**, *25*, 561–572.
49. Soares-Filho, B.; Rodrigues, H.; Follador, M. A hybrid analytical-heuristic method for calibrating land-use change models. *Environ. Model. Softw.* **2013**, *43*, 80–87.
50. Sangermano, F.; Eastman, J.R.; Zhu, H. Similarity weighted instance-based learning for the generation of transition potentials in land use change modeling. *Trans. GIS* **2010**, *14*, 569–580.
51. Soares-Filho, B.S.; Assuncao, R.M.; Pantuzzo, A.E. Modeling the spatial transition probabilities of landscape dynamics in an amazonian colonization frontier. *BioScience* **2001**, *51*, 1059–1067.
52. Overmars, K.P.; Verburg, P.H.; Veldkamp, T. Comparison of a deductive and an inductive approach to specify land suitability in a spatially explicit land use model. *Land Use Policy* **2007**, *24*, 584–599.
53. Cuevas, G.; Mas, J.F. Land use scenarios: A communication tool with local communities. In *Modelling Environmental Dynamics*; Paegelow, M., Olmedo, M.T., Eds.; Springer: Berlin, Germany, 2008; pp. 223–246.
54. Paegelow, M.; Olmedo, M.T.C.; Toribio, J.M. Cadenas de Markov, evaluación multicriterio y evaluación multiobjetivo para la modelización prospectiva del paisaje. *GeoFocus* **2003**, *3*, 22–44.

55. Pontius, R. Quantification error versus location error in comparison of categorical maps. *Photogramm. Eng. Remote Sens.* **2000**, *66*, 1011–1016.
56. Hagen-Zanker, A. An improved Fuzzy Kappa statistic that accounts for spatial autocorrelation. *Int. J. Geogr. Inf. Sci.* **2009**, *23*, 61–73.
57. Verburg, P.H. Simulating feedbacks in land use and land cover change models. *Landsc. Ecol.* **2006**, *21*, 1171–1183.
58. Mas, J.F.; Pérez-Vega, A.; Clarke, K.C. Assessing simulated land use/cover maps using similarity and fragmentation indices. *Ecol. Compl.* **2012**, *11*, 38–45.
59. Pontius Jr, R.G.; Boersma, W.; Castella, J.t.; Clarke, K.; de Nijs, T.; Dietzel, C.; Duan, Z.; Fotsing, E.; Goldstein, N.; Kok, K.; *et al.* Comparing the input, output, and validation maps for several models of land change. *Ann. Reg. Sci.* **2008**, *42*, 11–37.
60. Hayashida, F.M. Archaeology, ecological history, and conservation. *Ann. Rev. Anthropol.* **2005**, *34*, 43–65.
61. Houghton., R. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* **1999**, *51*, 298–313.
62. Li, X.; Dodson, J.; Zhou, J.; Zhou, X. Increases of population and expansion of rice agriculture in Asia, and anthropogenic methane emissions since 5000BP. *Quat. Int.* **2009**, *202*, 41–50.
63. Williams, M. Dark ages and dark areas: Global deforestation in the deep past. *J. Hist. Geogr.* **2000**, *26*, 28–46.
64. Kohler, T.A.; Cockburn, D.; Hooper, P.L.; Bocinsky, R.K.; Kobti, Z. The coevolution of group size and leadership: An agent-based public goods model for prehispanic Pueblo societies. *Adv. Compl. Sys.* **2012**, *15*, doi: 10.1142/S0219525911003256.
65. Etter, A.; McAlpine, C.; Possingham, H. Historical patterns and drivers of landscape change in Colombia since 1500: A regionalized spatial approach. *Ann. Assoc. Am. Geogr.* **2012**, *98*, 2–23.
66. Barton, C.M.; Ullah, I.; Mitasova, H. Computational modeling and neolithic socioecological dynamics: a case estudy from southwest Asia. *Am. Antiq.* **2010**, *75*, 364–386.
67. Fedick, S.L. Land evaluation and ancient Maya land use in the Upper Belize River area, Belize, Central America. *Lat. Am. Atiq.* **2012**, *6*, 16–34.
68. Gaillard, M.J.; Sugita, S.; Bunting, M.J.; Middleton, R.; Broström, A.; Caseldine, C.; Giesecke, T.; Hellman, S.E.V.; Hicks, S.; Hjelle, K.; *et al.* The use of modelling and simulation approach in reconstructing past landscapes from fossil pollen data: A review and results from the POLLANDCAL network. *Veg. Hist. Arch.* **2008**, *17*, 419–443.
69. Poska, A.; Sepp, E.; Veski, S.; Koppel, K. Using quantitative pollen-based land-cover estimations and a spatial CA_Markov model to reconstruct the development of cultural landscape at Rõuge, South Estonia. *Veg. Hist. Arch.* **2007**, *17*, 527–541.
70. Rogers, J.D.; Nichols, T.; Emmerich, T.; Latek, M.; Cioffi-Revilla, C. Modeling scale and variability in human–environmental interactions in Inner Asia. *Ecol. Model.* **2012**, *241*, 5–14.
71. Goldewijk, K.K. Estimating global land use change over the past 300 tears: The HYDE Database. *Global Biogeochem. Cycles* **2001**, *15*, 417–433.
72. Goldewijk, K.K.; Ramankutty, N. Land use changes during the past 300 years. *Land Use Land Cover Soil Sci.* **2004**, *1*, 1–22.

73. Foley, J.A.; Defries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; *et al.* Global consequences of land use. *Science* **2005**, *309*, 570–574.
74. Hurtt, G.C.; Frolking, S.; Fearon, M.G.; Moore, B.; Shevliakova, E.; Malyshev, S.; Pacala, S.W.; Houghton, R.A. The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Glob. Chang. Biol.* **2006**, *12*, 1208–1229.
75. Boyle, J.F.; Gaillard, M.J.; Kaplan, J.O.; Dearing, J.A. Modelling prehistoric land use and carbon budgets: A critical review. *Holocene* **2011**, *21*, 715–722.
76. Kohler, T.A.; Bocinsky, R.K.; Cockburn, D.; Crabtree, S.A.; Varien, M.D.; Kolm, K.E.; Smith, S.; Ortman, S.G.; Kobti, Z. Modelling prehispanic pueblo societies in theri ecosystems. *Ecol. Model.* **2012**, *241*, 30–41.
77. Murphy, J.T. Exploring complexity with the Hohokam Water Management Simulation: A middle way for archaeological modeling. *Ecol. Model.* **2012**, *241*, 15–29.
78. Peeters, H. Modelling mesolithic-meolithic land-use dynamics and archaeological heritage management: An example from the flevoland polders (The Netherlands). In *Beyond the Artifact: Digital Interpretation of the Past*; Niccolucci, F., Hermon, S., Eds.; Archaeolingua: Budapest, Hungary, 2010; pp. 14–17.
79. Barton, C.M.; Ullah, I.I.T.; Bergin, S.M.; Mitasova, H.; Sarjoughian, H. Looking for the future in the past: Long-term change in socioecological systems. *Ecol. Model.* **2012**, *241*, 42–53.
80. Gaillard, M.J.; Sugita, S.; Mazier, F.; Kaplan, J.O.; Trondman, A.K.; Broström, A.; Hickler, T.; Kjellström, E.; Kunes, P.; Lemmen, C.; *et al.* Holocene land-cover reconstructions for studies on land cover-climate feedbacks. *Clim. Past Discuss.* **2010**, *6*, 307–346.
81. Hurtt, G.C.; Chini, L.P.; Frolking, S.; Betts, R.A.; Feddema, J.; Fischer, G.; Fisk, J.P.; Hibbard, K.; Houghton, R.A.; Janetos, A.; *et al.* Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Chang.* **2011**, *109*, 117–161.
82. Olofsson, J.; Hickler, T. Effects of human land-use on the global carbon cycle during the last 6000 years. *Veg. Hist. Arch.* **2007**, *17*, 605–615.
83. Ruddiman, W.F.; Ellis, E.C. Effect of per-capita land use changes on Holocene forest clearance and CO2 emissions. *Quat. Sci. Rev.* **2009**, *28*, 3011–3015.
84. Lemmen, C.; Khan, A. A simulation of the neolithic trnasition in the Indus Valley. *Clim. Landsc. Civil.* **2012**, *198*, 107–114.
85. Patterson, M.A.; Sarson, G.; Sanrson, H.; Shukurov, A. Modelling the Neolithic transition in a heterogeneous environment. *J. Arch. Sci.* **2010**, *37*, 2929–2937.
86. Bray, D.B.; Ellis, E.A.; Armijo-Canto, N.; Beck, C.T. The institutional drivers of sustainable landscapes: A case study of the Maya Zone in Quintana Roo, México. *Land Use Policy* **2004**, *21*, 333–346.
87. McEvedy, C.; Jones, R. *Atlas of World Population History*; Penguin Books Ltd: Middlesex, England, 1978.

88. Aoki, K.; Shida, M.; Shigesada, N. Travelling wave solutions for the spread of farmers into a region occupied by hunter-gatherers. *Theor. Popul. Biol.* **1996**, *50*, 1–17.
89. Yan, M.; Wang, Z.; Kaplan, J.; Liu, J.; Min, S.; Wang, S. Comparison between reconstructions of global anthropogenic land cover change over past two millennia. *Chin. Geogr. Sci.* **2013**, *23*, 131–146.
90. DeFries, R.S.; Field, C.B.; Fung, I.; Collatz, G.J.; Bounou, L. Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. *Glob. Biog. Cycl.* **1999**, *13*, 803–815.
91. Ruddiman, W.F. The anthropogenic greenhouse era began thousands of years ago. *Clim. Chang.* **2003**, *61*, 261–293.
92. Etter, A. Las transformaciones de uso de la tierra y los ecosisemas durante el período colonial en Colombia (1500–1800). In *La economía Colonial de Nueva Granada*; Meisel, A., Ramírez, M.T., Eds.; TM Editores y Banco de la República, Bogotá: Bogotá, Hungary, 2013; p. 48.
93. Camacho, M.T.; Paegelow, M.; García Martínez, P. Retrospective geomatic landscape modelling. A probabilistic aproach. In *Modelling Environmental Dynamics*; Paegelow, M., Camacho Olmedo, M.T., Eds.; Springer: Berlin, Germany, 2008; pp. 247–268.
94. Dean, J.S.; Gumerman, G.J.; Epstein, J.M.; Axtell, R.; Sewdlund, A.C.; Parker, M.T.; McCarroll, S. Understanding Aansazi culture change through agent-based mdeling. In *Dynamics of Human and Primate Societies: Agent-Based Modeling of Sdocial and Spatial Processes*; Kohler, T.A., Gummerman, G.J., Eds.; Oxford University Press: Oxford, UK, 2000; pp. 179–206.
95. Wainwright, J. Can modelling enable us to understand the rôle of humans in landscape evolution? *Geoforum* **2008**, *39*, 659–674.
96. Zetina Gutiérrez, M.d.G. De la agroecología Maya a la arqueología demográfica: Cuántas casas por familia? *Estudios de cultura Maya* **2009**, *38*, 97–120.
97. Culbert, T.P. Población, subsistencia y el Colapso de los Mayas del Clásico. In *Simposio de Investigaciones Arqueológicas en Guatemala*; Laporte, J.P., Escobedo, H., Eds.; Museo Nacional de Arqueología y Etnología: Guatemala, Guatemala, 1995; pp. 666–672.
98. Parker, D.C.; Manson, S.M.; Janssen, M.A.; Hoffmann, M.J.; Deadman, P. Multi-agent systems for the simulation of land-use and land-cover change: A review. *Ann. Assoc. Am. Geogr.* **2003**, *93*, 314–337.
99. Parker, D.C.; Hessl, A.; Davis, S.C. Complexity, land-use modeling, and the human dimension: fundamental challenges for mapping unknown outcome spaces. *Geoforum* **2008**, *39*, 789–804.
100. Fisher, C.T.; Feinman, G.M.; Editors, G. In Focus: Landscapes over time: Resilience, degradation, and contemporary lessons. *Am. Anth.* **2005**, *107*, 62–69.
101. Scheffer, M. *Critical Transitions in Nature and Society*; Princeton University Press: Princeton, NJ, USA, 2009.
102. Nielsen, A.B.; Giesecke, T.; Theuerkauf, M.; Feeser, I.; Behre, K.E.; Beug, H.J.; Chen, S.H.; Christiansen, J.; Dörfler, W.; Endtmann, E.; *et al.* Quantitative reconstructions of changes in regional openness in north-central Europe reveal new insights into old questions. *Quat. Sci. Rev.* **2012**, *47*, 131–149.

103. Trondman, A.K.; Gaillard, M.J.; Mazier, F.; Sugita, S.; Fyfe, R.; Nielsen, A.B.; Twiddle, C.; Barratt, P.; Birks, H.J.B.; Bjune, A.E.; *et al.* Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling. *Glob. Chang. Biol.* **2015**, *21*, 676–697.