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Review

How Are Feedbacks Represented in Land Models?

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Abstract: Land systems are characterised by many feedbacks that can result in complex system behaviour. We defined feedbacks as the two-way influences between the land use system and a related system (e.g., climate, soils and markets), both of which are encompassed by the land system. Land models that include feedbacks thus probably more accurately mimic how land systems respond to, e.g., policy or climate change. However, representing feedbacks in land models is a challenge. We reviewed articles incorporating feedbacks into land models and analysed each with predefined indicators. We found that (1) most modelled feedbacks couple land use systems with transport, soil and market systems, while only a few include feedbacks between land use and social systems or climate systems; (2) equation-based land use models that follow a top-down approach prevail; and (3) feedbacks' effects on system behaviour remain relatively unexplored. We recommend that land system modellers (1) consider feedbacks between land use systems and social systems; (2) adopt (bottom-up) approaches suited to incorporating spatial heterogeneity and better representing land use decision-making; and (3) pay more attention to nonlinear system behaviour and its implications for land system management and policy.

Keywords: land system management and policy; resilience; adaptation; regime shifts; tipping points; nonlinear behaviours

1. Introduction

Land systems are shaped by the interplay between natural and human systems. As such, they reflect human efforts to secure a living in the biophysical environment [1–4]. Examples of these efforts include, but are not limited to, cultivation of food, construction of buildings, distribution of goods, and consumption of services. The ecological consequences of these activities are, for example, translocation of nutrients, altered hydrological systems and emission and sequestration of greenhouse gases. A land system can be considered as encompassing many related systems, with the land use system as the hub [5]. Therefore, dynamics in land systems are both the cause and the effect of interactions between land use systems and other related systems (see Figure 1). For example, economic growth can result in a change in price of agricultural commodities, which may have an impact on land use patterns. Sometimes these effects feed back to the initial driver: it may be that so many farmers decide to grow the crop of which the price increased, that the supply increases and the market price will decrease again. In other words, the roles of drivers and responses are not clearly separated: what started as being a response to a certain driver, may at a certain point affect the driver, therewith becoming a driver itself. Such two-way influences are generally called feedbacks. A general definition of feedback refers to 'a situation in which two (or more) dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled' [6]. In the scope of this paper, feedback in land systems can be defined as: a situation in which the land use system and a related system are connected together in such a way that they influence each other and their dynamics are thus strongly coupled. This definition fits in with our conceptualisation of a land system and best suits our needs for reviewing feedbacks in land systems.

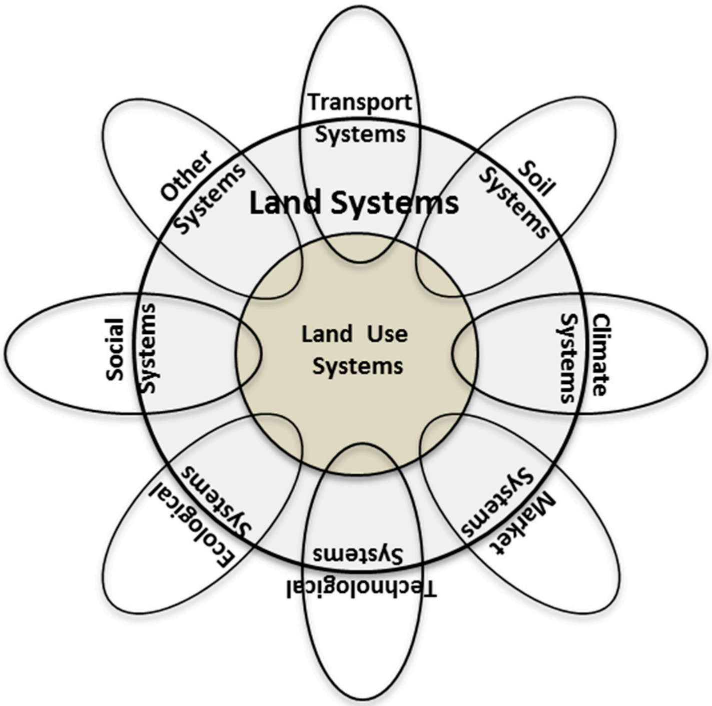

Figure 1. Land systems. At the centre of a land system is the land use system. Interacting with the land use system are the related systems: their dynamics are strongly coupled with dynamics in the land use system. Land systems encompass the land use system and parts of these related systems. These related systems can interact with each other, and may overlap (for simplicity, not reflected here). A feedback within a land system is a situation in which the land use system and a related system are connected together in such a way that they influence each other and their dynamics are thus strongly coupled (based on Aström and Murray [6]).

Feedbacks play an important role in the overall system behaviour. They can maintain the stability of the system [7], but sometimes cause an accelerated shift to a new system state [8]. They can strengthen or attenuate the impacts of driving forces, leading a system to respond differently than might be expected. For example, climate change could result in higher crop yields, leading to the anticipation of increased agricultural production in response to climate change. However, if demand remains constant, increased production might dampen prices, which could negatively feed back to producers, preventing or limiting any production expansion. Of more concern are probably positive feedbacks, which can accelerate a shift from one system state to another. An example is abandonment of farmlands in a marginal agricultural region: once a certain percentage of productive farmers have left their lands, infrastructure may collapse, raising the costs of continuing farming for those who remain, thus further accelerating abandonment. More generally, feedbacks potentially contribute to nonlinear behaviours [9] which are typical of complex systems and pose a major challenge to scientists and policymakers concerned with land system regulation.

To better understand land systems, we make use of computational models. Such models, however, were long devoid of feedback mechanisms, consisting only of one-way relationships between model components such as 'single linkages' and 'multiple unidirectional linkages' [10,11]. Two-way linkages [11] or loops [12] that represent feedbacks in land systems are nevertheless important to include. First, land models that have implemented feedbacks between model components better reflect the structure, function and dynamics of land systems as coupled human-environment systems [13]. Thus, land models with feedbacks incorporated are better equipped to explore and explain complex system properties such as nonlinear changes [14], specific spatial patterns [15] and land system behaviour that is otherwise difficult to explain or anticipate. Second, knowledge on feedbacks in land systems is essential to facilitate the transition towards sustainable development [16], and such knowledge can be gained via models that represent feedbacks. Recognition of the importance of representing feedbacks in scientific models grew during the 1980s, in parallel with the research agenda on climate change. Modelling techniques such as System Dynamics [17,18] and Discrete Event System Specification [19] proved useful to incorporate feedback mechanisms. Yet land models were generally not based on these approaches, as they do not allow for adequate spatial representation [20] of land use patterns (with a few exceptions [21,22] that coupled these approaches with a spatial component), which is crucial for understanding how systems function. Nonetheless, as appreciation of the importance of feedbacks in explaining phenomena in land systems grew [23], the need to incorporate them into land models became more evident. During the 1990s, conceptual representations of feedbacks started to appear in land models (e.g., IMAGE; [24]), though such feedbacks were often not made operational in the computational model. More frequently, land models were coupled with other models, for example, of soils [25–27] or of climate [28–30], but these attempts often ran afoul of scaling problems. The emergence of agent-based modelling, a tool designed especially to represent complex systems behaviour, was a step forward in implementation of feedbacks in models of land systems [31,32]. However, while complexity is considered to arise from both feedbacks between scale levels and interactions between agents, most agent-based models focused on the latter. Thus, the challenges of modelling feedbacks remain.

Despite the call for better representation of feedbacks in land models and the recognised difficulties, there is no overview available in the literature of the current state of the art regarding feedback representations in land models. From some existing reviews [10,31–44] on modelling applications and approaches in land systems that were published between 2002 and 2016, we found that the concept of feedback has received increasing attention and has been made more explicit (for details see Table S1). However, the knowledge on feedback representation in land models is still lacking, even though it has been suggested that those models were under way [31]. This paper aims to fill that gap by means of a literature review. As depicted in Figure 1, feedbacks may exist involving any coupling of the systems that are encompassed by the land system. Given the central status of the land use system in a land system [5], in this review we focus on feedbacks that connect the land use system with the related systems. Therefore, feedbacks without the participation of a land use system are outside the scope of this review. Specifically, we sought answers to three questions: (1) What feedback processes within land systems have been modelled? (2) How has feedback representation been achieved in the models? (3) To what extent has the modelling of feedbacks contributed insights into the complex systems behaviour of land systems? By answering these questions, the current research provides insights into the 'increasing capability for modelling and analysis of land systems' by highlighting and discussing the importance of feedbacks in land systems research.

2. Materials and Methods

2.1. Feedback in the Conceptual Model and Computational Model

We defined a land system as the aggregate of the land use system, parts of other related systems and their interactions (see Figure 1). The implementation of feedback in a computational model can be considered as a causal loop that specifies the two-way influences between a variable corresponding with a land use characteristic (e.g., cultivation intensity, crop type) and a variable that is part of a related sub-model. Figure 2 provides two examples of feedbacks that are represented in a conceptual model and implemented in a computational model.

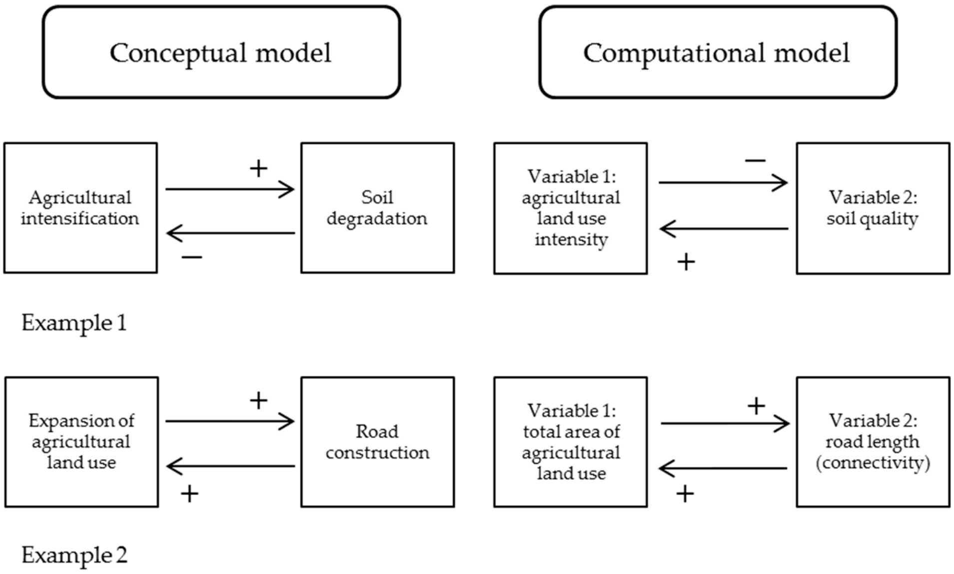

Figure 2. Examples of feedbacks in system conceptualisation and model implementation. Example 1: a negative feedback. (**Left**) Feedback between the process of agricultural intensification and the process of soil degradation. Intensification leads to soil degradation, which attenuates intensification. (**Right**) Implementation in computational model. Land use intensity and soil quality are the two linked variables that connect the sub-model of land use and the sub-model of soil. Increased land use intensity leads to reduced soil quality, which negatively feeds back to the intensity of agricultural land use. Example 2: a positive feedback. (**Left**) Feedback between the process of agricultural expansion and the process of road construction. They reinforce each other. (**Right**) Implementation in computational model. Total area of agricultural land use and road length are the two linked variables that connect the sub-model of land use and the sub-model of transport. Increased use of land leads to increased road construction at the expense of nature, which positively feeds back to the expansion of agricultural land use because of increased connectivity.

2.2. Literature Search

We conducted a comprehensive search of the ISI Web of Knowledge and Scopus for articles about land models that explicitly mention feedbacks in their title, abstract, or keywords (for the search in Scopus) or in the topics (for the search in the ISI Web of Knowledge). As search terms we used 'feedback' or 'feedbacks' combined with one of the following: 'land use model', 'land cover model', 'land change model', 'land use change model', 'land cover change model', 'land use allocation model', 'land use simulation', 'land cover simulation', 'land change simulation', 'land use change simulation', 'land cover change simulation', or 'land use allocation simulation'. The search encompassed the peer-reviewed journals in both databases and was done on 1 January 2016. Hence, all relevant articles published before 2016 were included. Additionally, we also included three articles that are highly related to this research but not found with our search due to the fact that 'feedback' is not mentioned in their title, abstract, or keywords. The earliest work dates to 1974. However, most reviewed articles were published after 2000.

This resulted in 56 articles. From the search results, we excluded one article reporting on a data collection tool, four review articles, three articles on models in which no feedback was described or implemented, ten articles in which the modelled feedbacks did not involve land (e.g., land use change was an exogenous variable that triggered a feedback between two climate variables) and one article on a model already included. This elimination resulted in a final sample of 37 articles.

2.3. Indicators Used

We defined a number of indicators to answer our research questions (Table 1). For the first research question, 'what feedback processes within land systems have been modelled?', we distinguished (1) the variables linked; (2) the major related system; and (3) the feedback character. 'Variables linked' refers to the sequence of variables connected by the feedback. It reflects the mechanics of causality and whether the feedback loop was closed in the computational model (indicated in Tables 1 and 2 by asterisks). A sequence of variables without a loop closure suggests a discrepancy between the conceptual model and the computational model, with the computational model not being in accordance with the conceptual model. 'Major related system' indicates the system that interacted with land use via the modelling of the 'variables linked'. These systems are not mutually exclusive but can interact with each other as well. However, the categorisation enabled us to report on the representation of feedbacks within land systems, according to the land system components and processes that are modelled. 'Feedback character' denotes whether the feedback can be labelled as positive or negative. A positive feedback arises when processes in the linked systems are reinforced by each other; negative feedback arises when one process attenuates another.

To answer the second research question, 'how has feedback representation been achieved in the models?', we examined for each article (1) whether it concerned a single model or a coupling of models; (2) the modelling technique; (3) discretisation of time; and (4) discretisation of space. All these indicators describe technical solutions for representing feedbacks between a land use model (component) and a related model (component). 'Single model vs. coupling' indicates whether the feedback was integrated within a single model or by coupling models, which might be defined at different spatial or temporal scales. 'Modelling technique' distinguishes between typical modelling techniques (e.g., equation-based, cellular automata and agent-based). We distinguished for each case if the modelling technique was applied to the whole-system level (thus a top-down approach) or to the agent or cell level (thus a bottom-up approach). 'Discretisation of time' denotes whether the model concerned was dynamic or non-dynamic. For dynamic models, we investigated the frequency (in the model time step) of updating the values of land use system variables and the variables of related systems, as well as the frequency of data exchange between models or model components. 'Discretisation of space' indicates whether the land use system variable was spatially aggregated to feed into another system, operating at a higher scale level, or if the other system operated at a finer scale level and its model output was aggregated to feed into the land use model.

For our third research question, 'to what extent has the modelling of feedbacks contributed insights into the complex systems behaviour of land systems?', we examined (1) the method of quantitatively assessing feedback; (2) how the land system reportedly responded; and (3) whether terminology associated with complex systems was used to describe system-level phenomena. 'Quantitative assessment of feedback effect' indicates the approach used to quantify the influence of the feedback on the land system. Table 1 lists multiple approaches. 'Classification of reported land system response' concerns whether the effects of feedback on the land use system were reported at all and, if so, how they were reported: in terms of magnitudes, in qualitative terms, or in both. Reports on magnitudes indicate the size of the feedback effect; while qualitative reports concern the nature of the effect and existence of nonlinear behaviours. Terminology related to complex systems includes regime shifts and tipping points, stable states, resilience, domains of attraction, nonlinearity, evolution and self-organisation, path-dependency, adaptation and recovery. Having considered that authors might have described system behaviours by using terms other than those specified in Table 1, we went through the result and discussion sections of all included articles to make sure all kinds of complex system behaviour descriptions were documented.

Table 1. Indicators and codes for feedback representations related to the three research questions: (1) What feedback processes within land systems have been modelled? (2) How has feedback representation been achieved in the models? (3) To what extent has the modelling of feedbacks contributed to insights into the complex systems behaviour of land systems?

Research Questions	Indicators	Codes
1	Variables linked	e.g., a-b-c * (with * indicating from c to a, thus a loop closure)
	Major related system	1. transport system (TS) 2. soil system (SO) 3. climate system (CS) 4. ecological system (ES) 5. market system (MS) 6. social system (SS) 7. technological system (TE) 8. other
	Feedback character	1. positive feedback 2. negative feedback
2	Single model vs. coupling	1. single model 2. coupling of models
	Modelling technique	1. top-down: equation-based 2. bottom-up: cellular automata 3. bottom-up: agent-based 4. top-down: scenario-based 5. top-down: rule-based 6. hybrid (specify each technique) 7. other
	Discretisation of time	model time step on land use system (years) model time step on related system (years) frequency of data exchange (years)
	Discretisation of space	1. the land use variable is aggregated to feed into the other variable 2. the other variable is aggregated to feed into the land use variable 3. both are aggregated 4. no aggregation
3	Quantitative assessment of feedback effect	1. no assessment 2. time series 3. comparison (of time series) against a reference 4. comparison (of time series) with feedback on/off 5. driver-state variable response relationship
	Classification of reported land system response	1. no report 2. report on the magnitude of the response 3. report on the nature of the response 4. report on both magnitude and nature of the response
	Use of terms related to complex systems	1. regime shift 2. stable states 3. resilience 4. domains of attraction 5. nonlinearity 6. evolution 7. path-dependency 8. self-regulation 9. adaptation 10. recovery

3. Results

Table 2 presents an overview of the results on the indicators for all reviewed articles. Figure 3 graphically summarises the findings, which are discussed in the following subsections.

Table 2. Overview of the reviewed articles (1: In cases where feedbacks were only discussed conceptually but not implemented in a computational model, there is no * at the end of the linked variables; 2: External drivers that are not modified by feedbacks are put in parentheses; 3: Explanations of variables and feedbacks are put in squared brackets; 4: ’_’ indicates information not available; ‘N’ indicates not applicable; ‘ND’ indicates not dynamic; 5: Time step and frequency of data exchange expressed in years; 6: For coding references, see Table 1).

Research Question	**1**						**2**				**3**	
Articles	**Variables Linked**	**Major related system**	**Feedback character**	**Single model vs. coupling**	**Modelling technique**	**Model time step in the land use system**	**Model time step in related system**	**Frequency of data exchange**	**Discretisation of space**	**Quantitative assessment**	**Classification of reported responses**	**Terms related to complex systems**
Putman, 1974 [45]	urban land development—traffic conditions—modified transport network *	1	1,2	2	1	15	15	15	4	4	2	2
Jones & O’Neill, 1992 [46]	cultivation labour, purchased inputs—soil degradation, productivity loss—conservation labour *	2	2	1	1	ND	ND	N	3	1	1	_
Leemans, 1995 [47]	(total primary energy consumption—) global agricultural land—global deforestation—atmospheric CO_2	3	_	2	4,5	10	_	_	1	1	1	5
Levinson, 1995 [48]	relocation of household and jobs—generated trips—traffic conditions *	1	2	1	1	1	1	1	4	1	1	6,7
Veldkamp & Fresco, 1996 [49]	percentage of five land use and cover types —erosion, soil fertility, plant disease *	2	2	1	1	3	3	3	2	4	2	_
Priess et al., 2001 [27]	crop types and area—carbon and nutrients in soil—soil fertility *	2	2	2	1,4	1	1	1	2	2	2	_
Rousseau & Clymer, 2002 [50]	transportation infrastructure investment—traffic pattern—composite impedance *	1	1	2	1	_	_	_	4	1	1	_
Soares-Filho et al., 2002 [51]	individual cell states and transition probability—macro-level land use pattern—distances to major land use types *	_	_	1	2	1	1	1	_	3	2	6
Parker & Meretsky, 2004 [52]	parcel-level presence of land for urban or agriculture—macro-level land use pattern—externalities—rent *	5	2	1	3	_	_	N	1	4	4	2,5,7
Gupta et al., 2006 [53]	(construction of priced toll road—) traffic time and costs—relocation of households and jobs *	1	1	2	1	5	5	5	4	3	2	_
Waddell et al., 2007 [54]	relocation of household and jobs—accessibility *	1	2	2	3,4	1	3–5	3–5	4	3	2	7

Table 2. *Cont.*

Research Question	1						2				3	
Articles	**Variables Linked**	**Major related system**	**Feedback character**	**Single model vs. coupling**	**Modelling technique**	**Model time step in the land use system**	**Model time step in related system**	**Frequency of data exchange**	**Discretisation of space**	**Quantitative assessment**	**Classification of reported responses**	**Terms related to complex systems**
Wu et al., 2007 [55]	crop type and area—crop price* [major feedback]; crop type and area—yield *	5	2	2	1	5	5	5	1	2	4	_
Koch et al., 2008 [56]	grazing area and intensity—stocking rate—landscape productivity *	2	1	2	1	5	1	5	2	3	2	8
Claessens et al., 2009 [25]	percentage of different land use and cover types and their locations—soil depth *	2	2	2	1	1	1	1	2	2	2	_
Moreira et al., 2009 [57]	land use demand defined by regional level—land use supply at local level *	_	1	2	1,3	1	1	1	_	1	2	_
Xu et al., 2009 [58]	area and location of land use for crop, forest, grass, and other—soil organic matter, and soil nitrogen content—suitability of soil *	2	2	2	1,4	1	1	1	2	4	2	10
Duthie et al., 2010 [59]	(future locations of jobs and housing—future trips—) traffic conditions—assessment of uncertainty—whether or not to improve certain part of highway *	1	_	2	1	_	_	_	4	1	1	_
Strengers et al., 2010 [30]	area and location of different land cover types—land–climate interactions via surface albedo—surface temperature	3	_	2	1	1	1	1	1	1	1	5
Devaraju et al., 2011 [60]	area of forest [deforestation]—temperature, precipitation, and soil carbon and productivity *	3	2	2	1	1	1	1	1	3	4	2,3,6,10
Kitchen et al., 2011 [61]	zone-level population and employment and site values—accessibility—modification on transport network *	1	1	2	3	1	6–10	6–10	4	1	1	6,7
Priess et al., 2011 [62]	policy on agricultural expansion—area of agricultural land—water available for irrigation *	3	2	2	5	1	1	1	1	4	2	_
Tóth et al., 2011 [63]	land used for conservation or development—price of land *—biodiversity	5	1	1	1	_	_	N	1	4	2	_
Martin & Levine, 2012 [64]	area and location of major land use and cover types—dust radiative effects—regional precipitation *	3	1,2	2	1,4	_	_	_	1	2	2	6
Güneralp et al., 2012 [65]	local scale land availability—regional investment rate—land change at local level *	5	1	2	1,1	2	2	2	1	4	2	_

Table 2. *Cont.*

Research Question	**1**											
							2				**3**	
Articles	**Variables Linked**	**Major related system**	**Feedback character**	**Single model vs. coupling**	**Modelling technique**	**Model time step in the land use system**	**Model time step in related system**	**Frequency of data exchange**	**Discretisation of space**	**Quantitative assessment**	**Classification of reported responses**	**Terms related to complex systems**
Le et al., 2012 [12]	area of croplands—income—socio-economic profile—land use decision models *	6	1	1	3	1	1	N	1	4	4	3,5,7,9
Pendyala et al., 2012 [66]	land use [relocation of housing and jobs]—travel demand—traffic pattern * [loop 1, back to travel demand]—network conditions *[loop 2, back to land use]	1	2	2	3	–	–	–	4	1	1	–
BenDor et al., 2013 [67]	(population growth)—new residential development—park service gap—political pressure—park development * [loop 1, back to park service gap]—land attractiveness for new development * [loop 2, back to new residential development]	6	1,2	1	1	1	1	N	1	2	2	–
Jones et al., 2013 [68]	land use and emissions—temperature	3	–	2	4	15	5	15	1	1	1	–
Murray-Rust et al., 2013 [69]	area and location of both urban and agricultural land—inequality in perceived residential quality of life (composed of green space, distance to shops, and noise) *	6	1	1	3,4	1	1	1	1	3	2	5,7,8,9
Oliveira et al., 2013 [28]	deforestation/agricultural expansion—precipitation—soil water—productivity	3	–	2	4	–	–	–	1	1	1	3
Robinson et al., 2013 [70]	exurban development and land management strategies—carbon storage and fluxes *	2	1,2	2	3	1	1	1	3	1	1	–
Zhang et al., 2013 [71]	land use planning decision—land use change [in scenarios]	6	–	1	3,4	1	–	N	1	1	1	–
Pongratz et al., 2014 [72]	LULCC fluxes—albedo, latent heat flux—CO_2 concentrations and temperature *	3	–	2	1	–	–	–	1	4	2	5
Su et al., 2014 [73]	density of population and employment—travel impedances [based on distance and network]—traffic minimising goal * [if not, back to land use allocation]—accessibility and congestion measures	1	2	2	5	–	–	–	4	3	2	–
Connor et al., 2015 [74]	(global) prices of agricultural products—agricultural land use changes *	5	2	2	1	1	1	1	1	4	2	6,9
Guillem et al., 2015 [75]	farm level land use regime (crop type) —intermediate model variables (vegetation height and harvestable biomass)—skylark population	4	–	2	3,4	1	1	1	4	1	1	2,9
Tsai et al., 2015 [76]	agents' financial conditions—expected utilities from food production and other ecosystem services—land use decisions—ecosystem services for food production and other services *	6	1,2	1	3	1	1	N	1	3	2	7

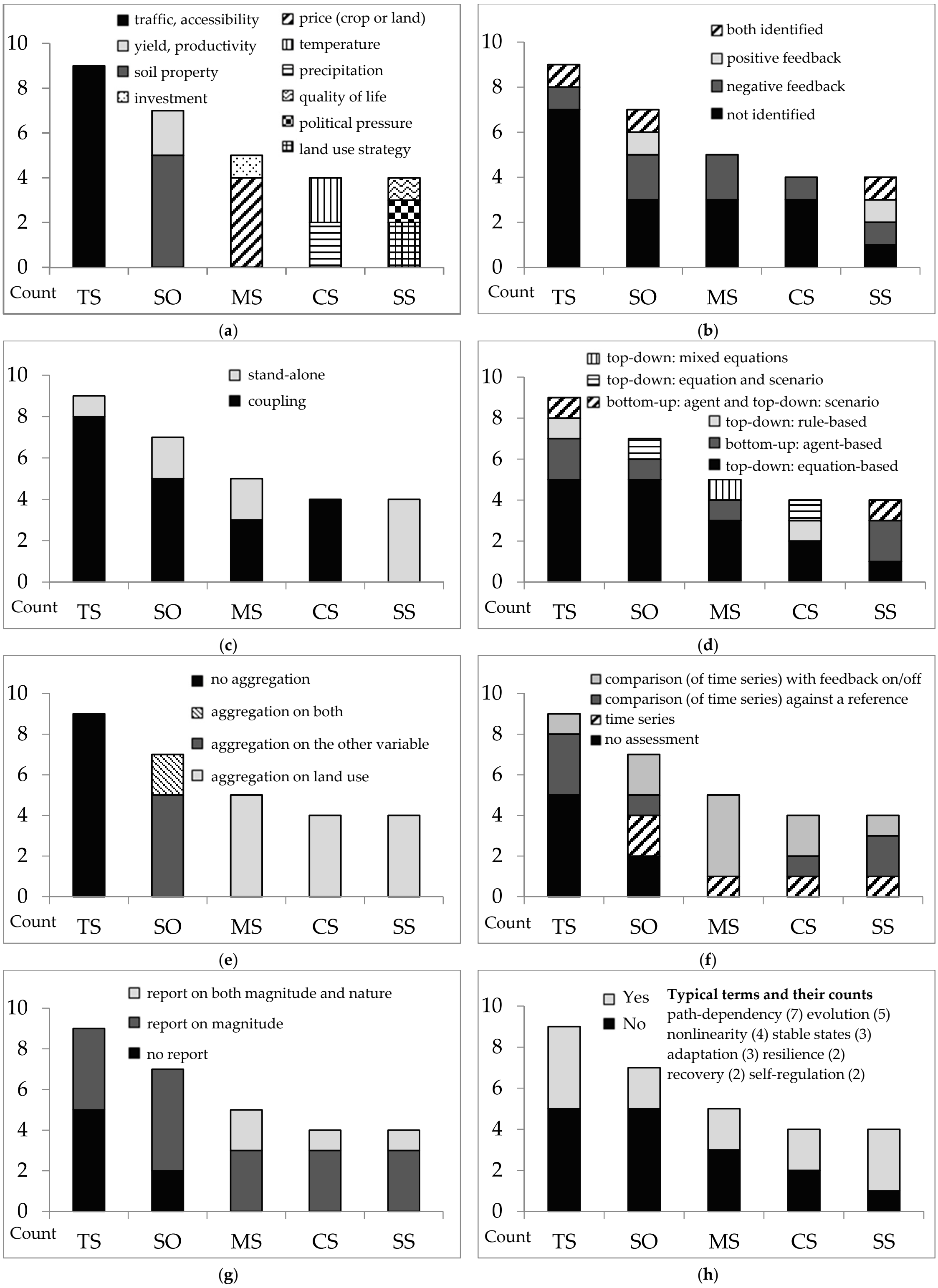

Figure 3. (**a**–**h**). Representation of feedbacks in the reviewed models, according to the related systems addressed. Note (1) TS: transport system, SO: soil system, MS: market system, CS: climate system, and SS: social system; (2) Cases that discussed feedbacks only conceptually without implementing them in a computational model are omitted. (**a**) major 'variables linked'; (**b**) feedback character; (**c**) how feedbacks were made operational; (**d**) modelling techniques; (**e**) discretisation of space; (**f**) assessment of feedback effects on the land system; (**g**) classification of reported land system response; (**h**) use of complex system terms to describe model outcome.

3.1. Feedback Processes between Land Use Systems and Related Systems

Most of the modelled feedbacks coupled the land use system to transport systems (9), soil systems (7), market systems (5), climate systems (4) and social systems (4) (Figure 3a). The models representing feedbacks between land use systems and transport systems made up the largest category. Some of them showed how residential land use evolved in response to the opening up of rural areas by road construction, and how this, in turn, led to further road construction (e.g., [45,50,53,61]). Others showed how specific urban land use patterns resulted in traffic congestions or lack of accessibility and how the response from road construction resulted in alleviated traffic conditions (e.g., [48,54,59,66]). The second-largest category of models represented feedbacks between agricultural land use and the soil system, via processes such as soil erosion, carbon sequestration or emission and water flows. These models typically depicted responses of the land use system to deterioration of soil functions due to (intensive) land use (e.g., [25,49,58]). Models representing feedbacks between land use systems and markets made up the third category. These showed the influence of land use on prices of agricultural products or land, and how land use, in turn, responded to the simulated changes in prices (e.g., [52,55,63]). The fourth category was made up of models representing feedbacks between land use and climate. Such models typically showed how land use systems could contribute to or mitigate climate change by affecting temperature (via evapotranspiration, heat flux, albedo, or convection), CO_2 (via carbon emissions or sequestration), and/or precipitation (via evapotranspiration), and how these climate changes, in turn, affected land use and management (e.g., [60,62,64]). The fifth category of models was those representing feedbacks between land use and social institutions. These demonstrated how land use changes can give rise to policy change (via formal institutions such as government or nongovernmental institutions, e.g., [67]) and behavioural change (via informal institutions such as social networks [12], altered financial conditions [76], or perceived quality of life [69]), which could result in land use changes in turn. In the reviewed articles, no models were found to represent feedbacks between land use and technological systems. One of the reasons could be the tradition of regarding technology as a driving force of land change processes [77].

The timeline of the publications (Figure 4) shows that transport systems and soils systems have received constant attention in land models. The inclusion of market systems in land models shows a clear increase over time. Both climate systems and social systems were only recently linked with land use systems via feedbacks in models. For climate systems, there were earlier attempts to link them with land use systems (see Table 2). However, these attempts did not represent the links as feedbacks but rather as one-way relationships in their computational models. All models that linked social systems and land use systems via feedbacks were found in very recent studies.

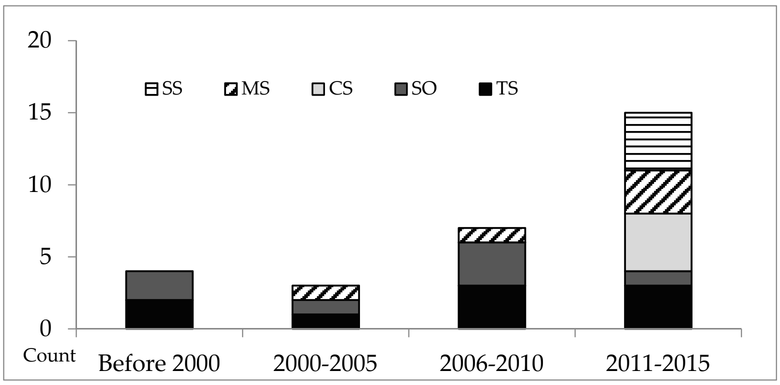

Figure 4. Trend of systems linked with land use systems via feedbacks in models. TS: transport system; SO: soil system; MS: market system; CS: climate system; and SS: social system.

Two articles were excluded from further analysis because upon closer examination they appeared not to simulate feedback processes or did not provide information on implementing feedbacks in their models. The paper by Soares–Filho et al. [51] described an iterative calculation scheme for mimicking a certain pattern or trend. Their claimed feedback seems to be in the dynamic variables (distance to major land use types) that depend on the land use change process. This did not match with our definition of feedback. The paper by Moreira et al. [57] coupled two land use models operating at different scale levels, but provided no description of how they were coupled. These two studies were therefore not included in the figures.

For the articles in which feedbacks were identified, most of them simulated negative feedbacks, meaning that development of one variable was reversed or slowed down by the development of another variable. Few feedbacks were positive, meaning that development of one variable was reinforced by the development of another variable. There was no obvious indication that particular categories of related systems displayed more negative (or positive) feedbacks than others (Figure 3b).

3.2. Representation of Feedback in the Models

Feedbacks were more commonly formalised by coupling existing models than by linking variables within a single (stand-alone) model (Figure 3c). All feedbacks between land use and climate were formalised by coupling models. This is perhaps explained by the large difference in scale between the climate and land use systems. Feedbacks between land use systems and social systems were all formalised within single models. This is probably because models that represent social processes are still at a nascent stage. Feedbacks between the land use system and transport system, soil system and market system were formalised either by coupling models or by linking variables within a single model.

Investigation of the techniques used for modelling indicated that whole-system, equation-based models that follow a top-down approach constitute the majority in virtually all categories (Figure 3d), followed by agent-based models that follow a bottom-up approach, hybrid models (among which there was a mix of equation-based, agent-based and scenario-based models) and rule-based models with a top-down approach. Modelling techniques, moreover, appeared to have become more diverse in recent years (Figure 5). Among the techniques used in these recent studies in Figure 5 (2011–2015), agent-based models seem to be the most popular to address land system related feedbacks.

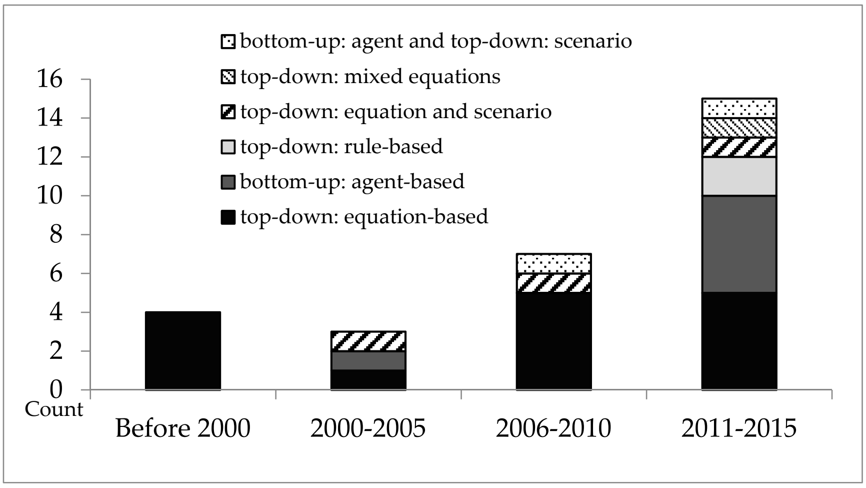

Figure 5. Trend of modelling techniques.

The majority of models were dynamic (not shown in the figures). The only non-dynamic model was that in Jones and O'Neill [46] of land use and soil degradation. This model described the equilibrium state that arose after a feedback process had taken place. The model was not explicit about how feedbacks take place. Questions remained unaddressed, for example, about the composition of flows between entities (information, matter) and the time elapsing before equilibrium comes about. For the dynamic models, a yearly model time step was typically used for the land use system (Table 2).

For the coupled models, the elapsed time between data exchanges between the state of the land use model and the related system model was mostly determined by the time step of the land use model, suggesting temporal aggregations on the state of the related systems which used a finer temporal resolution (e.g., [56], see Table 2). In a few cases land use system variables were aggregated temporally to feed into models of a related system (e.g., [61], see Table 2).

Discretisation of space is shown in Figure 3e. For the models linking land use with climate, markets, and social systems, the land use system variables were spatially aggregated to feed into the models (or model components) of the related systems; for the models linking agricultural land use with the soil system, soil properties were spatially aggregated to feed into the land use models (or model components); for the models linking land use with transport networks, no aggregations were observed as they operated on the same scale. Aggregations on both land use system variables and soil variables were found in the non-dynamic model, which did not capture the process of feedback and showed effects only for the equilibrium state.

3.3. Reported Effects of Feedback

The majority of the models quantitatively assessed the effects of the feedback (Figure 3f). Some of these assessments were based only on time series (e.g., [25,27,55,64,67]). Others compared a model outcome, either as time series or as a specific snapshot, against a reference (e.g., an officially adopted forecast that did not include feedbacks [54]; a different grazing regime scenario [56]; or a control simulation using a different land use scenario [60]). The rest compared model outcomes, either as time series or as a specific snapshot, by turning on and off the feedback mechanism (e.g., [58,62,63,65]). In other cases, no effects of feedback were reported for any systems, as the articles described only model construction.

Responses of land systems were discussed either in terms of the magnitude of the response or in terms of both the magnitude and the nature of the response (Figure 3g). Most of the reviewed cases fell into the first type. Magnitudes were termed as, for example, 'substantial difference' [45], 'significant expansion' [27] or 'significant difference' [54] and 'strong effect' [56]. Only four cases provided qualitative descriptions of the response. For example, Parker and Meretsky [52] and Devaraju et al. [60] observed stable states, Parker and Meretsky [52] and Le et al. [12] observed nonlinearity and Wu et al. [55] observed fluctuations.

Terms related to complexity and complex systems were used to describe system-level behaviours in 14 of the 29 cases with formalised feedbacks (Figure 3h). 'Regime shifts', 'tipping points' and other terms for describing complex systems behaviour, however, were not observed or represented in the reviewed cases. There was no obvious trend in use of terms related to complex systems (Figure 6).

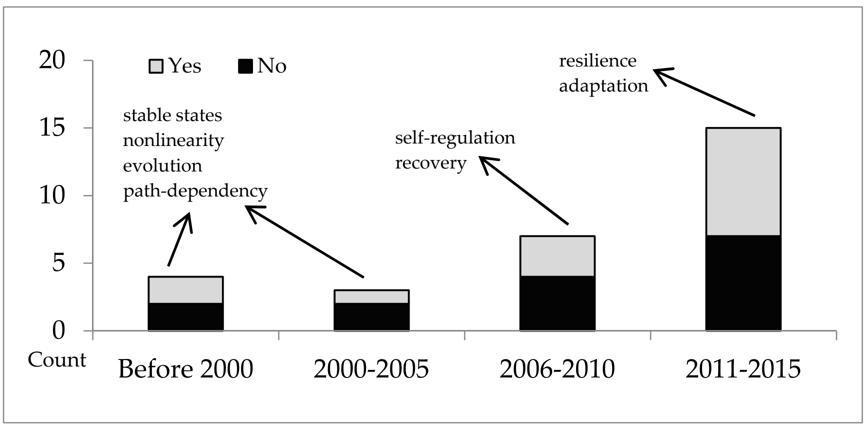

Figure 6. Trend in use of terms related to complex systems to describe land system behaviours. Terms used are connected by arrows to the time period in which their first appearances were found in the reviewed articles.

4. Discussion

The search strategy we employed for this review limited our findings to those articles on land models that explicitly claim to include feedbacks. This search strategy probably yielded only a subset of all models that actually incorporate some form of feedback. We believe, nevertheless, that based on this subset several valuable conclusions can be drawn with respect to the research questions.

4.1. What Drives the Modelling of Feedbacks that Involve Land System Processes?

The collection of land models discussed here integrates a range of systems (transport systems, soil systems, market systems, climate systems and social systems) with land use systems through feedback processes. A question that emerges is what has driven the researchers to couple particular systems, thereby making use of particular modelling techniques. Obviously, the conceptualisation of a particular feedback between two systems is driven by a research question, and the formulation of a relevant research question is driven by the background of the modeller. An exploration in Scopus of the ten authors who published most articles with 'land use' in the title suggests that land use scientists tend to have a background in soil science, physical geography, landscape ecology, biology, or (environmental or agricultural) economics. This may be explained by the following reasons: (i) assessing yields is an important element in rural land use models, which requires knowledge of biophysical growing conditions; (ii) the study of land use change was, for a while, strongly linked with the study of land cover change, an activity based on the interpretation of satellite images, which is typically a topic for physical geographers and the like; (iii) scientists with a background in natural sciences tend to be more acquainted with the use of computational models; and (iv) the (spatially explicit) data that is required for calibrating and validating models is easier to obtain for biophysical system properties (e.g., from remote sensing) than for societal system properties. These are possible explanations for the abundance of models representing feedbacks between land use systems and soil systems, and to a lesser extent, between land use systems and climate systems and between land use systems and market systems. However, the abundance of models that link land use systems with biophysical systems does not imply that links between land use systems and societal systems are less pertinent. The modelling of these links is, however, hindered by more demanding data collection procedures and a general lack of a modelling tradition amongst social scientists (other than economists). Nevertheless, the emergence of agent-based modelling techniques suggests a restoration of this (presumed) backlog, as this modelling technique typically allows the representation of social–psychological mechanisms [78,79] that deviate from economic optimisation behaviour (e.g., see [80,81]). The recent emergence of this type of modelling suggests that feedbacks with other societal systems are still to be explored, such as feedbacks between land and refugees from (land related) conflicts or climate change, feedbacks between land and ageing populations and between land and climate change but via social processes (e.g., perception, awareness [41]) rather than via physical processes.

4.2. How Are Land Changes Represented?

Our investigation suggests that land use system modelling techniques are largely based on 'whole-system' equations that follow a top-down approach (Figure 3d). The question emerges whether this is because the top-down, whole-system approach is the most appropriate method for simulating feedbacks, or if this choice is instead driven by motivations such as ease of modelling or modelling traditions in particular scientific fields. After all, scientific disciplines concerned with soil, climate, market equilibrium and traffic flows have a tradition of equation-based modelling [82–85] at the system level, which could explain the abundance of 'whole-system' equation-based feedback simulations reviewed here. Besides, other plausible reasons of using 'whole-system' equation-based modelling could be the ease of data collection, the nature and type of the available data and the sufficiency or accuracy of simulating certain processes that are part of the feedback mechanism. However, whole-system equation-based models tend to neglect spatial heterogeneity of both landscapes and land users, which are important factors in land systems [86,87]. In some cases this shortcoming was addressed by applying the equations to spatially disaggregated units [88,89]. Such models are similar to agent-based models that follow a bottom-up approach, although they are devoid of the interactions that are a typical feature of agent-based models. Agent-based models, which were used in eight cases in our sample, represent processes at the individual (land user) level and incorporate heterogeneous behaviours as well as social interaction [36], although the representation of social interaction of the reviewed models was observed only in Le et al. [12]. As such, agent-based models have the ability to deal with temporal and spatial dimensions, making them highly suitable for simulating feedbacks between land use and other systems. There are nevertheless disadvantages as well: their data demand and computational costs are high, especially when they need to cover large spatial and temporal scales [90]. This could explain the absence of agent-based models in cases where a land use change process is simulated to influence coupled systems in which processes operate at a wide spatial scale, such as climate change and policy change. In other words, agent-based land models are usually applied in cases where the spatial and temporal extents are comparatively small.

In the cases where a top-down approach (whole-system equation-based models) was used, we suspect that the land use change process has itself been subject to oversimplification, compared to the other simulated process (such as soil degradation or climate change). This is in fact reported in a review of models coupling land and climate [43] that points out the disadvantage of top-down, whole-system approaches and calls for decision-based land models, even on the global scale. We propose the same for models that address feedbacks within land systems for two main reasons: (1) the coevolution of land change and other linked processes requires the land system to learn and adapt, which is best supported by a bottom-up approach such as agent-based models; (2) an agent-based land model can be more easily coupled with heuristic models that have not been formalised mathematically [91], for example, in the social sciences. This review covers a few examples of such models. Agents' financial conditions [76], requirements on certain type of land use [67], behavioural strategies [12] and perceived quality of life due to land use changes [69] have been explored by agent-based models.

4.3. How Are the Effects of Feedbacks Explored?

Despite the various techniques for exploring feedback effects, most model outcomes were not explicitly used to improve knowledge on the complex behaviour of land systems. Investigations of the relationship between the modelled feedback and nonlinear model outcomes did not receive substantial attention in the majority of the reviewed articles. Time series had limited utility in aiding management and policy intervention, as driver-response relationships were not revealed. Comparisons between model outcomes and a reference served either to validate the model or to compare different modelling approaches. Comparisons between model outcomes derived by turning feedbacks on and off quantified the difference an implemented feedback made in the land system. These model outcomes, however, were not specifically used to provide information about nonlinear behaviours in land systems or to support policy recommendations on managing such nonlinearities.

Terms such as path-dependency, nonlinearity, stable states and resilience were used to describe the complex behaviours of the modelled systems (Figure 3h). Among the complex systems terminology, path-dependency was mentioned the most. This is no surprise as it is an obvious characteristic of process-based and stochastic models. Less often mentioned were terms such as stable states and nonlinearity, with even fewer appearances of terms such as resilience, recovery and self-regulation. However, the relationship between the modelled feedbacks and these complex systems properties were not explored, despite the occasional mention of those properties. It remains to future studies to determine whether the simulated feedbacks contribute to model outcomes that demonstrate these complex behaviours. None of the articles reported model outcomes indicative of nonlinear system-level behaviour, such as regime shifts and tipping points. This suggests that the added value of the implemented feedbacks warrants further exploration in future research.

5. Conclusions

This review found, first, a wide range of feedbacks captured in land models. The modelled feedbacks linked land use systems to transport systems, soil systems, market systems, climate systems and social systems. These representations of feedbacks in land models allow for the exploration of land system behaviours in the dimensions of society, economy and environment. The inclusion of feedback in the reviewed land models was influenced by aspects such as research questions, background of the modellers, modelling tradition, ease of data collection and model coupling, as well as social relevance and importance. A challenge for future representations of feedbacks in land models is to include processes in related systems that have so far been ignored. Some examples are feedbacks between land and refugees from (land related) conflicts or climate change, feedbacks between land and ageing populations and between land and climate change but via social processes rather than physical processes.

Second, the dominant use of top-down, whole-system, equation-based modelling techniques suggests a relatively poor representation of decision-making processes underlying land use change, which could be improved by bottom-up modelling techniques. Future land models with specific interest in understanding how feedback affects the land system are thus challenged to better represent land use decision-making processes from bottom-up.

Third, the reviewed articles explored the effects of formalised feedbacks in various ways, but issues of nonlinearity or complexity arising from feedbacks were seldom mentioned. System-level phenomena such as regime shifts and tipping points were not mentioned in any of the reviewed articles. Thus, we recommend that in future land models more attention should be paid to nonlinearity from a complex systems perspective and to the implications of nonlinearity for land system management and policymaking.

Supplementary Materials: The following is available online at http://www.mdpi.com/2073-445X/5/3/29/s1, Table S1: An overview of reviews concerning feedbacks in land systems.

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