Behavioural models of climate change adaptation and mitigation in land-based sectors

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Authors:

Full name and affiliation; email address if corresponding author; any conflicts of interest

First author Calum Brown*, University of Edinburgh, calum.brown@ed.ac.uk; no conflict of interest
Second author Peter Alexander, University of Edinburgh; no conflict of interest
Third author Sascha Holzhauer, University of Edinburgh; no conflict of interest
Fourth author Mark D A Rounsevell, University of Edinburgh; no conflict of interest

Abstract

Models of the land system are essential to our understanding of the magnitude and impacts of climate change. These models are required to represent a large number of processes in different sectors, but face particular challenges in describing the individual and social behaviours that underpin climate change mitigation and adaptation. We assess descriptions of these behaviours in existing models, their commonalities and differences, and the uses to which they have been put. We find that behavioural models have a distinct and important role to play in climate research, but that they currently suffer from being strongly sectoral in nature, with agricultural models being the most common and behaviourally rich. There are also clear convergences, with economic-based decision-making remaining dominant and behaviours such as diffusion, interaction, anticipation or learning remaining relatively neglected. Active climate change is also rarely modelled, with adaptation and mitigation generally represented as responses to economic drivers under static climatic conditions. Furthermore, dynamic behaviours, objectives or decision-making processes are almost entirely absent, despite their clear relevance to climate change responses. We conclude that models have been more successful in the identification of important processes than in their implementation and that, while some behavioural processes may remain impossible to model, behavioural models of adaptation and mitigation in land-based sectors have substantial unexplored potential. We suggest that greater attention be paid to the cumulative coverage of models in this field, and that improvements in the representation of certain key behaviours be prioritised.

Introduction

Climate change poses various challenges to the ways in which society uses land[1,2]. It has impacts on land use that necessitate adaptation, but is also strongly affected by biogeochemical and biophysical interactions with the land surface[3]. Changes in land use are therefore at the forefront of climate change mitigation and adaptation, as well as mediating climatic impacts on other human and natural systems. The potential for mitigation and adaptation in different land-based sectors is the subject of intense scrutiny[4–6], but is not purely technical in nature. At a fundamental level, this potential depends upon the ability and willingness of people to act, individually and collectively[7–9].

Models have transformed our understanding of climate system dynamics, and are similarly required to illuminate climate-land interactions[10–12]. To date, the majority of suitable models have treated the land system as economic, reflecting the advanced state of economic modelling, the dominance of economics in theoretical accounts of global human activity, and the marginalisation of other (e.g. environmental) factors in large-scale practical decision-making[10,13]. However, these models typically neglect important forms of individual and social behaviour, resulting in hidden uncertainties that interact and propagate through modelled systems[3,10]. This articles assesses the extent to which models have been and can be used to explore these uncertainties by incorporating more realistic forms of behaviour in land-based mitigation and adaptation decisions.

A great deal of evidence now shows that the capacity to mitigate or adapt depends upon a wide range of social factors such as levels of education, literacy, cohesion and equality[7,11,14–16], and upon political rights and structures[17–19]. Individual adaptations or mitigations further depend upon, for example, values, knowledge and perceived personal efficacy[13,20–25]. Indeed, subjective perceptions of change and responsive choices may not align well with concepts of mitigation and adaptation that appear obvious to an outside observer[26,27], instead passing through “several layers of institutional, moral and symbolic meaning”([15]p.76), each of which may be interpreted differently by the various actors involved[28,29].

Political, economic and other macro-scale drivers of land use are not immune from behavioural issues either. They can be affected by the values and norms of institutional actors’ internal and external milieus[30], by spontaneous changes on the demand-side such as increasing ‘environmental rationality’[13,31], or by broader changes in social structures[32] - all effects that can be expected under climate change[8,33,34]. As these effects occur, the scope for mitigation and adaptation at lower levels will also be altered[35–38]. Perhaps the most significant implication of this interactive dynamism is that models that perform well in current behavioural, social, economic and other contexts do not necessarily have relevance in the contexts of the near future[29,39]. There is a consequent, general risk of over-fitting to current conditions and taking insufficient account of their potential for change.

The complex social setting in which adaptation and mitigation occur means that models inhabited by populations of *homo economicus* can easily mislead. Models that take better account of individual and social behaviour do exist, and have developed rapidly in recent years (although their application to questions related to climate change has been more limited[10,11,40]). These include a range of agent-based, multi-agent, microsimulation and similar approaches that prioritise ‘bottom-up’ (or interactional upward and downward) process accuracy in describing land system development (such models are reviewed by, e.g.,[41–43]). However, the extent to which any model can provide accuracy in this context is debatable. Certainly, none can fully capture the culturally-mediated perceptions about what is “believable, desirable, feasible and acceptable”[27, p.87] that determine real-world decision-making. Furthermore, the treatment of these perceptions as filters of an external reality that is objectively describable may be challenged[27,29,44,45], with a full understanding perhaps requiring the immersive techniques of anthropology[27].

Notwithstanding the fact that limits to the ability of models to represent climate adaptation and mitigation clearly exist, behavioural modelling retains great importance for our understanding and management of these processes. While forswearing complete accuracy, it has a capacity for representation and projection that can provide unique insights that are complementary to those of the social sciences and biophysical models. Furthermore, Earth systems models make assumptions about human behaviour by definition, whether or not those assumptions are explicit or economic in nature, and the exploration of alternative assumptions is essential to understanding their effects.

Here, we review models designed to represent human behaviour in mitigation and adaptation in land-based sectors. We do so in order to assess the realised and potential value of such models. We identify the applications that exist, their commonalities and differences, and their implications for the field as a whole. We use our findings to describe the coverage of current models and some obvious and important gaps that limit their contribution. This also highlights important processes that are absent from non-behavioural models in the field, and implies certain biases in their results. We use these findings to briefly discuss the future role of behavioural modelling in climate research.

METHODS

We identified models designed or used to study behavioural processes in mitigation or adaptation in land-based sectors (we did not explicitly include the special case of urban development, which is the subject of a largely separate literature). These were primarily identified through ISI Web of Knowledge searches (initially in September 2015 and updated in July 2016) using the following groups of keywords: (‘land use’ or ‘land cover’ or ‘land based’ or ‘agriculture’ or ‘agricultural’ or ‘forest’ or ’restore’ or ‘restoration’ or ‘conservation’ or ‘rewild’ or ‘ecosystem’) and ‘climate change’ and (‘behaviour’ or ‘behavior’ or ‘behavioural’ or ‘behavioral’ or ‘agent’) and (‘model’ or ‘modelling’ or ‘modeling’). All phrases were included both with and without hyphenation, as appropriate, and all papers published since 2000 were included. These searches returned 1,806 papers. From these, we removed papers that did not include behavioural modelling or climate change (following separate examination of titles, abstracts and entire papers), and added cited papers that had not appeared in the original searches. This left a total of 45 papers (excluding discussion or review papers). For each of these papers, we recorded details about the modelling undertaken, the behavioural processes and actors included, forms of mitigation or adaptation permitted, modelled impacts of climate change, and methods of validation or uncertainty estimation. We did not formally assess model transparency or availability.

REVIEW FINDINGS

Adaptation or mitigation

At a general level, a majority of behavioural models focus on processes of adaptation rather than mitigation (Table 1). Active mitigation in a changing climate (either in terms of lessening climate change or lessening the impacts of climate change) is rarely treated, even where models focus on relevant processes such as reforestation or the adoption of bioenergy crops (e.g.[46–49]). Instead, mitigation is represented as an economic process driven by taxes or subsidies designed to reduce greenhouse gas emissions[48–55]. In some cases, economically-driven mitigation is balanced against climatically-driven adaptation[51,54,56]. No models consider either risks or processes of maladaptation, despite these being obvious and important subjects for behavioural modelling[40].

Within models of adaptation, agricultural crop selection is a common focus, with both the nature and timing of arable agricultural activities being varied[39,57], often in response to reductions in water availability[58] (adaptation to flooding, primarily in urban areas, is a separate focus[59,60]). Adaptation in pastoral agriculture is less commonly treated (e.g.[61]), as is adaptation in commercial forestry (e.g.[62,63]). However, a number of models do consider the broader effects of adaptation on competing land uses or between human and natural processes in the land system[51,64–67]. More varied is the modelled nature of the adaptation process, with some placing greater emphasis on social, rather than individual, factors[68–71], or short-term risk minimisation rather than long-term planning[71,72].

Sectoral coverage

Agriculture

Of all land-based sectors, agriculture is the principal focus for behavioural models of adaptation (Table 1, Figure 1). These usually focus on arable agricultural management options[49,57,58,67,71,73–75] and timings[39,58,72], although some models include broader decisions related to intensification and extensification[55,65,76], buying or selling of land[77] or competition between arable and pastoral agriculture[39,67]. Though less common, a number of models consider competition between agriculture and other land uses such as forestry[50,51,56,64] or urban development[66]. Most agricultural models allow decision-making on the basis of direct climatic impacts, but several (especially cross-sectoral models) simulate responses to taxes or subsidies designed to encourage adaptation or mitigation[48,49,51–54,75,76]. These decisions tend not to be subject to social pressures, except in studies of communal or marginal agriculture (e.g.[68]) or of water resource management[36,58,78,79].

Forestry

Generally, models of the forestry sector are not as numerous as models of agriculture, and this imbalance is also present in models that consider climate change and, especially, human behaviour. In fact, changes in forestry are often modelled as a simple consequence of changes in agriculture, or as purely economic responses to taxes or subsidies[20,46,51,56,65,80]. This paucity of modelled forms of management and behaviour does not necessarily impede consideration of some kinds of mitigation or adaptation[81], but it does mean that their full variety and complexity cannot be considered. A few models have put forestry in the context of cross-sectoral, large-scale adaptive decisions in land management[50,51,54,56,63], but we found only two that focused on adaptation within forestry[62,63], to maintain yields, economic benefits or, potentially, ecosystem characteristics[63]. This clear gap in model applications is curious given forestry's socio-economic and environmental importance, and its strong interactions with the climate system manifest in forestry-based mitigation options.

Nature Conservation

A considerable literature has accumulated about the social contexts and implications of nature conservation, especially the ways in which environmental and socio-economic objectives can be allied (e.g.[82–84]). However, there have been very few attempts to consider the ways in which relevant social structures, attitudes or behaviours might vary under climate change, or what the effects of these variations might be. We found one model that represents decisions by conservation NGOs to buy land from farmers in a changing climatic and institutional context[77], but in the other rare cases where environmental objectives are included, conservation is treated as secondary to decisions about agriculture or forestry[50,65].

Water management

A substantial subset of models highlight or focus entirely on the water sector. A common theme is the complexity of this sector, with many different actors being involved at many different organisational levels[59,85]. In some cases this complexity is presented as a substantial barrier to modelling, better captured through scenario development than simulations[58,85], although some attempts have been made to simulate limited interactions between actors[86]. One of the main foci of these models is the use of water for agriculture in specific settings, such as water rights frameworks in Chile[36,87] or reservoir management in Brazil[58]. Others focus on the potential for adaptation in domestic water supply[69,86], while a third group address flood control, especially in coastal areas where rivers and urban centres co-exist[59,60,88]. Many of these models acknowledge inadequacies in their treatment of water management, and it is clear that interactions with other sectors have not been fully explored.

Subsistence agricultural land uses

Land use or management for subsistence can reasonably be considered as distinct from other sectors. Not only are different sets of economic, socio-cultural and personal drivers involved at different spatial scales but, because of an inherent lack of adaptive or mitigative capacity, responses to changes in climate will also differ[21,72]. This distinction is borne out in the modelling literature, with models tending either to focus exclusively on subsistence management or to neglect it entirely (but see [54]), with the latter approach being more common. Where subsistence land uses are considered, they are usually treated as closely related to social structure, highlighting interactions between climate change, social change and land management decisions[68,70,89]. These interactions are complex and explorations of them have been limited, however, with some models of marginal agriculture dealing only with individual behaviour[37,61,75].

General land use change – cross or non-sectoral

The great majority of models are applied to specific geographical and land-use contexts, but some are designed to include general, theoretical or cross-sectoral processes. These include wholly abstract changes in land management[53,90], changes that span a range of specific sectors but include little detail within them[64], or competition between sectors in specific contexts (see above). Despite these examples, substantial, cross-sectoral changes and their drivers are clearly under-represented, and there remains considerable uncertainty about how best to balance behavioural richness and generality, both theoretically and methodologically.

Climate Change impacts & responses

Most models include only one form of climate change impact, usually on water resources that affect agricultural crops[36,50,57,58,61,66,68,71,77,88], flooding[59,60] or other sectors such as tourism[69]. Less frequently included are other climatic effects on crop yields[54,65,72,76] or on agricultural management activities[39]. In models of forestry, impacts are usually purely economic (in terms of timber prices and/or subsidies and taxes)[51,53,62] but may extend to yields[56] and even broader ecosystem characteristics[63]. Otherwise, cross-sectoral impacts are included only once in the models we considered, where they affect ecosystem functioning, resource harvests and, indirectly, community composition and adaptive capacity[89].

Some models do not include the direct impacts of climate change, and some do not include direct responses. In the latter class, several models focus on responses to policies (for mitigation[48,49,51,52,55], or adaptation[75]). Generally, however, specific sectoral responses to specific sectoral impacts are included, especially in forestry[62] and water management for flood control[59,60]. In agriculture, responses are usually expressed through crop choices and changes in the timings of activities[58,68,71,72,75]. Modelled responses are often notably cross-sectoral, however. In several cases, changes are permitted between arable and pastoral agriculture, between agriculture and other land uses (often forestry), or between use and abandonment of land[37,39,50,51,53–56,61,64,66,77,91]. Broader still are options for adaptation through general resource usage[36,69,89], adoption of technology[69], mitigation of poverty[73], engagement with social or institutional responses[89], or migration[57,88,89,92]. In sum, modelled responses to climate change are therefore substantially more diverse than the modelled impacts of climate change, suggesting a clear opportunity for further, cross-sectoral impacts to be considered.

Actors & Processes

Behavioural entities and processes are at the core of the models we reviewed, and treatments of them can be very detailed as a result. Unsurprisingly, the most commonly-modelled actors in behavioural models are individual land managers. These are usually represented using agent-based approaches, with greater or lesser degrees of interaction between the agents (Table 1). Other commonly modelled entities include households (either representing cohabiting individuals or a unit of land) or institutions such as government agencies. There are substantial methodological challenges in the parameterisation of such agents, especially over large geographical extents, and attempts to address these challenges are ongoing (e.g.[93]). The majority of models we consider do not attempt to advance methodology in this respect (excepting, recently, the increased use of role-playing games for model calibration or validation[54,76]), but use established forms of model architecture and parameterisation in novel contexts. Nevertheless, the design and emphases placed on different behavioural processes vary widely (Figure 1), suggesting a lack of agreement about which processes are important under climate change, and how they should be modelled. Below, we consider the main behavioural factors included in the models we review and the extent of convergence in their implementation.

Diffusion

Diffusion of knowledge, attitudes or practices between neighbouring or socially-connected individuals is recognised as a fundamental process in all human systems. Many models of land-based sectors include it, and the ability to represent it explicitly is seen as a major advantage of bottom-up modelling approaches[87,94,95]. It can therefore be expected to play a substantial role in models of the kind we consider, given the importance of information and innovation in adaptation or mitigation in land-based sectors. Many of the models we reviewed do include diffusion of agricultural practices or technology[37,47,49,51,66,69,76,79], but fewer include diffusion of information or attitudes, or diffusion in other sectors[50,53,60,71] (forestry models were particularly lacking in this respect, including only indirect spatial influences between agents). These latter models are of particular interest where they allow behaviour to change with social (and, potentially, climatic) context, rather than modelling static behaviour within a dynamic environment. This is a key element of adaptation in particular, and is included in terms of socially-mediated attitudes to climate change[70], levels of trust in weather forecasts[71], or choices between economic and social objectives[53]. While the absence of socially-driven behavioural change may be a shortcoming of some behavioural models, studies that include diffusion suggest a more basic problem in non-behavioural models. This stems from the fact that diffusion takes time to occur, slowing the speed of adoption of new practices and technologies. Depending on the timescales involved, this could have very significant consequences for the timing and success of adaptation or mitigation actions. The exploration of these consequences therefore appears to be a key contribution of the behavioural models reviewed here.

Institutions

Institutions (which we use here to mean informal social structures as well as formal organisations or actors) play a decisive, but highly complex and sometimes opaque role in land management decisions and responses to climate change. This is regularly acknowledged in modelling papers, but is also used to excuse a subsequent neglect of institutional actors and effects. In some cases it is explicitly argued that scenarios of institutional interventions are more transparent and appropriate than attempts to model institutional behaviour (e.g.[85]), and this certainly seems a logical minimum requirement for models intended to evaluate policy options[49,50,52,54–56,75,76,96].

Most papers are not explicit about the choices involved in selecting and designing institutional agents, but a limited number of such agents is often included. In the simplest cases, these represent particular actors that can monitor and intervene in land use change in some way, for example government bodies[37,60,66], banks[60] or businesses[69]. Alternatively, households and communities have been represented as institutions with their own adaptive strategies [57,89] or capacities[70]. Others have proposed far more extensive institutional representations, with individuals, communities, companies, regulating authorities and governmental bodies all playing different, but interactive roles[59,86,88]. However, the most commonly modelled institution is a market for goods, land or water[36,73,77,79].

Although there are few synergies in the representations of institutional actors, there are some strong commonalities. Considerable attention is paid to governmental taxation, subsidisation, regulation and information dissemination[37,49,54,55,60,66,75,76], and these are often included as exogenous factors even in the absence of modelled institutional agents. The role of social structures in the diffusion of technology, information, practices and behaviour is emphasised[40,53,69] (see above), and some attribute more importance to the effects of such structures than to individual decision-making (especially in studies of the water sector[59,69,85,97] or in marginal or subsistence settings[11,36,40,64,68,86,89]). Nevertheless, representations of institutional actors are usually (and avowedly) simplistic. While a wide range of institutions have been modelled in total, little has been done to explore alternative – or more complete – representations of the institutional landscape, or to investigate potential changes in institutional objectives or relationships through time (but see[57,98]).

Learning & anticipation

The ability to learn from past experience is an important component of adaptive capacity. Nevertheless, a surprisingly large number of behavioural models do not include any form of learning. Of those that do, roughly half allow agents to learn from their own experiences, to a greater or lesser extent[37,47,60,68,86], and half supplement individual learning with social learning on the basis of neighbours' experiences, perceptions or beliefs[51,53,59,70,71,87]. One model was used to study optimal timescales of learning for reactive adaptation[72], but none included further temporal change in learning processes. Most strikingly, no models implemented any form of second-order learning, in which experiences could alter agents' decision-making rules or objectives (with the exception of social influences on priorities[53]).

Anticipation of future economic or climatic conditions is also rarely addressed, but a small number of models include it on the basis of forecasts[68,71], existing knowledge and experience[50,56–58,62,63,86,99] or uncertain perceptions of risk[59,60]. In one case, expectations were weighted by length of tenure[56], but other temporal variations again remain unconsidered. This is a significant omission given the known importance of anticipation in motivating mitigation or adaptation[13,21,22].

Type of decision-making

Social and behavioural factors of the kinds discussed above have generally acknowledged importance in climate change adaptation and mitigation, and this is reflected by the inclusion of at least one of these factors in the majority of relevant models. However, while these factors often inform the decisions made by model agents, their exact roles and importance varies widely and often without detailed justification, except where determined by data availability (e.g.[55,75,76]). Furthermore, despite the explicitly behavioural focus of models included in this review, the majority assume some form of economic rationality as the basis for land management decisions. This varies from rigid optimisation or equilibrium[51,52,56,62,72,78] to heterogeneous, partial or time-dependent satisfaction of economic objectives[39,48,49,55,57,60,65–68,75–77,100,101]. A (substantial) minority of models prioritise social or environmental factors, sometimes on the basis of empirical evidence[37,50,51,53,64,69]. As a result, the potential of many models to capture behavioural effects on adaptive capacity appears to be largely unrealised. Almost none are presently able to consider linked changes in social and climatic conditions, and their implications for future decision-making, despite this being technically feasible[89].

Validation & Uncertainty

Validation of behavioural models of land-based sectors is not a simple task. Theoretically, validation may be technically impossible in complex human (and natural) systems because unique causality is not necessarily present or provable[102,103]. Practically, a general lack of suitable or sufficiently extensive data limits validation options[104]. There is some agreement that replication of observed outcomes risks over-fitting and that validation should therefore focus on process accuracy as far as possible[29,39,71,102]. These issues are especially pertinent to behavioural models of climate change because, on the one hand, neither climatic (and hence environmental) nor behavioural conditions can be assumed to stay constant, while on the other hand the complexity of these conditions can generate an effectively endless array of spurious results if inadequately constrained.

Despite the importance of validation, it is not always carried out or even discussed (and a lack of transparency often makes subsequent validation impossible)[1,105]. Where validation does occur, it often takes the form of tuning or ‘calibration’ of models to consistently replicate observed outcomes. Rigorous discussion or application of validation procedures is not uncommon[36,56,87,99,106], but has not led to consistency of practice or development of methodology. In the models we reviewed, five main approaches to model validation or evaluation were apparent: checking modelled behaviour against actors’ stated or revealed behaviour[36,50,56,68,71,76,87,107] (comparisons of the two[25] were not used); extensive sensitivity analyses[36,39]; comparison (or tuning to ensure agreement) of some modelled and measured outcomes[37,39,57,58,60,66,78,87,89,107]; comparison to the results of other models[73]; and reliance on previous validation of the same or a similar model[51,53,58,65,69] (Figure 2). Justification of the (usually single) selected approach is rare, as is discussion of implications for model usage and interpretation.

A closely related issue is uncertainty in model results. Some see this as a key consideration in behavioural modelling, because systematic exploration of uncertainties is necessary for models to inform robust policies or management strategies[39,59,86,99,108]. At the other extreme, uncertainty may be entirely neglected[57,61,62], although explicit justifications for this, such as potential detraction from the force of general findings (e.g.[109]), or irrelevance to the task of improved understanding (e.g.[54]) is very rare. Between these extremes, a range of approaches are adopted, including discussion of potential uncertainties[54,63], the use of a number of social and environmental scenarios[65,69], analyses that build on unstructured collections of runs[51,64,70], structured (e.g. Monte Carlo) approaches[36,37,56,71,89], and mathematically rigorous explorations of parameter space[39]. Once again, the diversity of approaches limits the scope for general conclusions or cross-model comparisons to be established[110]. This problem is exacerbated by a tendency for the least behaviourally rich models to make the most confident predictions, overlooking the uncertainties (or even inaccuracies) inherent in their basic assumptions[111]. This adds considerably to the recognised difficulties of describing uncertainties in climate projections because it obscures the form and potentially the existence of uncertainties in land system contributions to climatic change[112].

Discussion & Conclusion

Climate adaptation and mitigation decisions are shaped by their social as well as environmental, economic and political contexts[7,13,16,27]. However, models of the linked development of the climate and land systems have tended to prioritise descriptions based on economic rationality, with relatively little work done to explore the inaccuracies resulting from this approach. In principle, established forms of behavioural models are well-suited to this task because they are designed to represent many of the processes known to be key to adaptation and mitigation. However, it is less clear whether existing models achieve the potential of this approach. In reviewing published behavioural models of climate change adaptation or mitigation in land-based sectors, we are able to identify a number of areas that have received considerable modelling attention, and a number that have received very little. In fact, the latter group is particularly large and significant, containing many types of behaviour that are known to have strong and pertinent effects. This may suggest some theoretical, as well as practical, limits to the scope for modelling the effects of climate change in human systems, but appears to leave substantial unexplored potential.

At a very general level, it is clearly both necessary and possible to move beyond excessively or indiscriminately economic approaches (which have been described as "implausible caricatures…as prescribed by the rationality theory, with a touch of psychological realism in the best possible case" [113], p.4). That is not to say that economic processes are unimportant, or even adequately represented in all cases, but they are at least widely included using clear, interpretable assumptions (if not justifications). The same is not true of behavioural processes, and there remains considerable scope for exploring the effects of known[9,38,71] or theorised forms of behaviour[13,113]. Many of these behaviours are social in nature, particularly where land uses are part of either very complex or very constrained social systems (e.g. where many actors are present or where poverty and deprivation are particularly intense[11,59,69,85,97]). Equally important are dynamic behaviours and social structures that allow for realistic interactions between actors and their environments. In order for models to account for true adaptation - including in the nature, objectives and forms of individual and social behaviours – they need to prioritise generative cognitive processes over more tractable optimisation functions[113,114].

Of course, it is not necessarily the case that ever-greater behavioural accuracy is either desirable or possible. Not all forms of individual and social behaviours are amenable to modelling, but the identification of limits is a complex problem involving philosophical and practical considerations[26,27,29,115]. For example, it may not be possible to usefully simulate the decisions of any particular individual but perfectly possible to explore the effects of particular forms of decision-making, and while culture may not be reducible to model algorithms, specific differences in perceptions can be. This reflects the value of behavioural models in providing controlled experimental settings for improving understanding; a role based on interpretability and exploration rather than attempted descriptive or predictive accuracy[29,116]. Certainly, the use of behavioural models to understand effects beyond the scope of economic models is well-supported and relatively common across land system science[3,10,93,117,118]. This often involves simple models that can illuminate areas of uncertainty or potential developments that were previously unrecognised[11,22,81,86,119]. Obvious and achievable contributions here include assessments of the role of diffusion in attitudes, knowledge or uptake of novel practices[47,95], the potential for particular aspects of local knowledge to alter the impacts of global drivers of change[54,70,120,121], and the effects of changes in ecosystem service provision on societal and individual decision-making[70,89,119].

More comprehensive analyses face the challenge of incorporating social and ecological systems dynamics more fully[7,63,72]. While this challenge is not insurmountable, it may require methodological advances alongside complementary approaches such as participatory modelling[54,76,122,123] and socio-ecological systems modelling[63,122,124]. Such developments could allow valuable advances in exploring the implications of socially-constructed beliefs, perceptions and resilience, particularly for adaptation options that might wrongly appear feasible or rational to an outside observer, or for an increased likelihood of maladaptation to objective climate impacts[26,115,125]. Broader techniques are required to move beyond highly specific single applications and represent entire, integrated socio-economic, climatic and environmental systems[12,63,86,90,126] (largely beyond the scale of current applications; Figure 3). Defining and describing these systems is, inevitably, extremely difficult[127], but there are a number of clear steps that can be taken towards this end. The first is to adopt consistent approaches across land-based sectors, so that cross-sectoral models properly represent the interactive processes involved. This requires, for example, models of forestry and pastoral agriculture that approach the richness of models of arable agriculture, including both mitigation and adaptation, dynamic rather than static climatic conditions, and a broader range of behavioural processes[63,80,128]. The simulated impacts of climate change must be broader too, so that diverse responses to a realistic range of different impacts can occur together. A clear priority here is the treatment of water resources, which are currently the subject of a specialised and largely separate modelling literature (and one that emphasises the importance of institutional actors).

Finally, some general issues of modelling practice, apparent in the models we reviewed (though certainly not unique to them), also prevent models from achieving their full potential. The first concerns transparency, with models often being poorly described and unavailable for further analysis – a particular problem where prototype models are presented, but not subsequently implemented. This has distinct implications for behavioural models to the extent that written descriptions of behaviour sometimes diverge quite significantly from programmed descriptions, making it hard to determine what exactly has been simulated. Secondly, uncertainty in model results is rarely analysed or described in detail, despite the considerable uncertainty inherent in behavioural model design and calibration. More robust handling of uncertainty is essential, especially where models are intended to support real-world decision-making[105,129]. Thirdly, there remains a disconnect between the identification and modelling of factors important to climate change mitigation and adaptation. Models are rarely founded on a clear conceptualisation of these processes, and frequently fail to account for the ways in which they differ from 'ordinary' land use change.

It is important to recognise that many of these criticisms relate to behavioural modelling of climate change mitigation and adaptation in sum, rather than to individual instances that are necessarily limited in scope. Furthermore, many apply equally to non-behavioural models that make unrealistic assumptions about human behaviour. The neglect of non-economic and social behaviours such as diffusion, anticipation and learning in any model suggests an unexplored bias towards artificially rapid responses to economic stimuli and a lack of responses to social or environmental stimuli. Projections of linked changes in climate and land use are therefore likely to be excessively homogeneous, temporally discrete and amenable to simple political interventions. However, it is obvious that some boundaries need to be set if models are to be practicable, and these boundaries will inevitably be artificial in a system as complex as that of the Earth System, its inhabitants and its climate. The greatest gains may therefore be made simply through better recognition of behavioural modelling as a necessary, coherent and distinct area of climate change research, fostering communication between practitioners and systematic methodological developments on clear philosophical foundations.

References

1. Rosa, I. M. D., Ahmed, S. E. & Ewers, R. M. The transparency, reliability and utility of tropical rainforest land-use and land-cover change models. *Glob. Chang. Biol.* **20,** 1707–1722 (2014).
2. Pielke, R. A. *et al.* Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdiscip. Rev. Clim. Chang.* **2,** 828–850 (2011).
3. Rounsevell, M. D. A. *et al.* Towards decision-based global land use models for improved understanding of the Earth system. *Earth Syst. Dyn. Discuss.* **4,** 875–925 (2013).
4. Porter, J. R. *et al.* in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (eds. Field, C. B. et al.) 485–533 (Cambridge University Press).

5. Noble, I. R. *et al.* in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (eds. Field, C. B. et al.) 833–868 (Cambridge University Press).

6. Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. M. & C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. T. in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. [Edenhofer, O., R., Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. & Savolainen, S. Schlömer, C. von Stechow, T. Z. and J. C. M.) (Cambridge University Press, 2014).

7. Crane, T. A., Roncoli, C. & Hoogenboom, G. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. *NJAS - Wageningen J. Life Sci.* **57,** 179–185 (2011).

8. Dovers, S. R. & Hezri, A. A. Institutions and policy processes: the means to the ends of adaptation. *Wiley Interdiscip. Rev. Clim. Chang.* **1,** 212–231 (2010).

9. Gifford, R., Kormos, C. & McIntyre, A. Behavioral dimensions of climate change: drivers, responses, barriers, and interventions. *Wiley Interdiscip. Rev. Clim. Chang.* **2,** 801–827 (2011).

10. Levis, S. Modeling vegetation and land use in models of the Earth System. *Wiley Interdiscip. Rev. Clim. Chang.* **1,** 840–856 (2010).

11. Nay, J. J., Abkowitz, M., Chu, E., Gallagher, D. & Wright, H. A review of decision-support models for adaptation to climate change in the context of development. *Clim. Dev.* **6,** 357–367 (2014).

12. Miller, B. W. & Morisette, J. T. Integrating research tools to support the management of social-ecological systems under climate change. *Ecol. Soc.* **19,** 41 (2014).

13. Zehr, S. The sociology of global climate change. *Wiley Interdiscip. Rev. Clim. Chang.* **6,** 129–150 (2015).

14. Below, T. B. *et al.* Can farmers' adaptation to climate change be explained by socio-economic household-level variables? *Glob. Environ. Chang.* **22,** 223–235 (2012).

15. Feola, G., Lerner, A. M., Jain, M., Montefrio, M. J. F. & Nicholas, K. A. Researching farmer behaviour in climate change adaptation and sustainable agriculture: Lessons learned from five case studies. *J. Rural Stud.* **39,** 74–84 (2015).

16. Naess, L. O. The role of local knowledge in adaptation to climate change. *Wiley Interdiscip. Rev. Clim. Chang.* **4,** 99–106 (2013).

17. Yohe, G. & Tol, R. S. J. Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. *Glob. Environ. Chang.* **12,** 25–40 (2002).

18. Brooks, T. M. *et al.* Global Biodiversity Conservation Priorities. *Science (80-.).* **313,** 58–61 (2006).

19. Gupta, J. *et al.* The Adaptive Capacity Wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environ. Sci. Policy* **13,** 459–471 (2010).

20. Thompson, D. W. & Hansen, E. N. Carbon Storage on Non-industrial Private Forestland: An Application of the Theory of Planned Behavior. *Small-scale For.* **12,** 631–657 (2013).

21. Truelove, H. B., Carrico, A. R. & Thabrew, L. A socio-psychological model for analyzing climate change adaptation: A case study of Sri Lankan paddy farmers. *Glob. Environ. Chang.* **31,** 85–97 (2015).

22. García de Jalón, S., Silvestri, S., Granados, A. & Iglesias, A. Behavioural barriers in response to climate change in agricultural communities: an example from Kenya. *Reg. Environ. Chang.* **15,** 851–865 (2014).

23. O'Brien, K. L. & Wolf, J. A values-based approach to vulnerability and adaptation to climate change. *Wiley Interdiscip. Rev. Clim. Chang.* **1,** 232–242 (2010).

24. Ung, M., Luginaah, I., Chuenpagdee, R. & Campbell, G. Perceived Self-Efficacy and Adaptation to Climate Change in Coastal Cambodia. *Climate* **4,** 1 (2015).

25. Niles, M. T., Brown, M. & Dynes, R. Farmer's intended and actual adoption of climate change mitigation and adaptation strategies. *Clim. Change* **135,** 277–295 (2016).

26. Orlove, B. The past, the present and some possible futures of adaptation. (2009).

27. Roncoli, C., Crane, T. & Orlove, B. Fielding climate change in cultural anthropology. *Anthropol. Clim.* (2009).

28. Grothmann, T. & Patt, A. Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Glob. Environ. Chang.* **15,** 199–213 (2005).

29. Brown, C., Brown, K. & Rounsevell, M. A philosophical case for process-based modelling of land use change. *Model. Earth Syst. Environ.* **2,** 50 (2016).

30. Nilsson, A., von Borgstede, C. & Biel, A. Willingness to accept climate change strategies: The effect of values and norms. *J. Environ. Psychol.* **24,** 267–277 (2004).

31. Spaargaren, G. & Vliet, B. Van. Lifestyles, consumption and the environment: The ecological modernization of domestic consumption. *Env. Polit.* (2007).

32. Crenshaw, E. M. & Jenkins, J. C. Social Structure and Global Climate Change: Sociological Propositions concerning the Greenhouse Effect. *Sociol. Focus* **29,** 341–358 (1996).

33. Hastrup, K. Anthropological contributions to the study of climate: past, present, future. *Wiley Interdiscip. Rev. Clim. Chang.* **4,** 269–281 (2013).

34. Strauss, S. Are cultures endangered by climate change? Yes, but…. *Wiley Interdiscip. Rev. Clim. Chang.* **3,** 371–377 (2012).

35. Shandra, J. M., London, B., Whooley, O. P. & Williamson, J. B. International Nongovernmental Organizations and Carbon Dioxide Emissions in the Developing World: A Quantitative, Cross-National Analysis. *Sociol. Inq.* **74,** 520–545 (2004).

36. Arnold, R. T., Troost, C. & Berger, T. Quantifying the economic importance of irrigation water reuse in a Chilean watershed using an integrated agent-based model. *Water Resour. Res.* **51,** 648–668 (2015).

37. Zhang, T., Zhan, J., Huang, J., Yu, R. & Shi, C. An Agent-based reasoning of impacts of regional climate changes on land use changes in the Three-River Headwaters Region of China. *Adv. Meteorol.* **248194,** 1–9 (2013).

38. van Sluisveld, M. A. E., Martínez, S. H., Daioglou, V. & van Vuuren, D. P. Exploring the implications

of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technol. Forecast. Soc. Change* **102,** 309–319 (2016).

39. Troost, C. & Berger, T. Dealing with Uncertainty in Agent-Based Simulation: Farm-Level Modeling of Adaptation to Climate Change in Southwest Germany. *Am. J. Agric. Econ.* **97,** 833–854 (2014).

40. Patt, A. & Siebenhüner, B. Agent Based Modeling and Adaptation to Climate Change. *Vierteljahrshefte zur Wirtschaftsforsch.* **74,** 310–320 (2005).

41. Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G. & Gotts, N. M. Agent-based land-use models: a review of applications. *Landsc. Ecol.* **22,** 1447–1459 (2007).

42. 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.* **93,** 314–337 (2003).

43. An, L. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecol. Modell.* **229,** 25–36 (2012).

44. Winch, P. *The idea of a social science and its relation to philosophy*. (Routledge, 1958).

45. Purcell, T. & Onjoro, E. Indigenous knowledge, power and parity. *Approaches to Indig. Knowl.* (2002).

46. Dyer, G. A. & Nijnik, M. Implications of carbon forestry for local livelihoods and leakage. *Ann. For. Sci.* **71,** 227–237 (2013).

47. Alexander, P., Moran, D., Rounsevell, M. D. A. & Smith, P. Modelling the perennial energy crop market: the role of spatial diffusion. *J. R. Soc. Interface* **10,** 20130656–20130656 (2013).

48. Scheffran, J. & BenDor, T. Bioenergy and land use: a spatial-agent dynamic model of energy crop production in Illinois. *Int. J. Environ. Pollut.* (2009).

49. Brown, C., Bakam, I., Smith, P. & Matthews, R. An agent-based modelling approach to evaluate factors influencing bioenergy crop adoption in north-east Scotland. *GCB Bioenergy* **8,** 226–244 (2016).

50. Bell, A. R. Environmental Licensing and Land Aggregation: An Agent-Based Approach to Understanding Ranching and Land Use in Rural Rondônia. *Ecol. Soc.* **16,** (2011).

51. Morgan, F. J. & Daigneault, A. J. Estimating impacts of climate change policy on land use: an agent-based modelling approach. *PLoS One* **10,** e0127317 (2015).

52. Jiang, Y. & Koo, W. W. The Short-Term Impact of a Domestic Cap-and-Trade Climate Policy on Local Agriculture: A Policy Simulation with Producer Behavior. *Environ. Resour. Econ.* **58,** 511–537 (2013).

53. Matthews, R. B. & Bakam, I. A combined agent-based and biophysical modelling approach to address GHG mitigation policy issues. *Modsim 2007 Int. Congr. Model. Simul.* 4–10 (2007).

54. Salvini, G. *et al.* REDD+ and climate smart agriculture in landscapes: A case study in Vietnam using companion modelling. *J. Environ. Manage.* **172,** 58–70 (2016).

55. Ferreira, V. & Samora-Arvela, A. Soil erosion vulnerability under scenarios of climate land-use changes after the development of a large reservoir in a semi-arid area. *J.* (2016).

56. Kerr, S., Liu, S., Pfaff, A. S. P. & Hughes, R. F. Carbon dynamics and land-use choices: building a regional-scale multidisciplinary model. *J. Environ. Manage.* **69,** 25–37 (2003).

57. Malanson, G. P. *et al.* Changing crops in response to climate: Virtual Nang Rong, Thailand in an agent based simulation. *Appl. Geogr.* **53,** 202–212 (2014).

58. van Oel, P. R., Krol, M. S. & Hoekstra, A. Y. Application of multi-agent simulation to evaluate the influence of reservoir operation strategies on the distribution of water availability in the semi-arid Jaguaribe basin, Brazil. *Phys. Chem. Earth, Parts A/B/C* **47-48,** 173–181 (2012).

59. O'Connell, P. E. & O'Donnell, G. Towards modelling flood protection investment as a coupled human and natural system. *Hydrol. Earth Syst. Sci.* **18,** 155–171 (2014).

60. Putra, H. C., Zhang, H. & Andrews, C. Modeling Real Estate Market Responses to Climate Change in the Coastal Zone. (2015).

61. Liu, Y. C., Zhang, T., Geng, X. L., He, L. S. & Pang, Z. G. Herdsmen's Adaptation to Climate Changes and Subsequent Impacts in the Ecologically Fragile Zone, China. *Adv. Meteorol.* **Article ID,** (2013).

62. Hannah, L. *et al.* The impact of climate change on California timberlands. *Clim. Change* **109,** 429–443 (2011).

63. Rammer, W. & Seidl, R. Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes. *Glob. Environ. Chang.* **35,** 475–485 (2015).

64. Murray-Rust, D. *et al.* Combining agent functional types, capitals and services to model land use dynamics. *Environ. Model. Softw.* **59,** 187–201 (2014).

65. Gimona, A., Poggio, L., Polhill, J. G. & Castellazzi, M. Habitat networks and food security: promoting species range shift under climate change depends on life history and the dynamics of land use choices. *Landsc. Ecol.* **30,** 771–789 (2015).

66. Yan, D. *et al.* Interactions between land use change, regional development, and climate change in the Poyang Lake district from 1985 to 2035. *Agric. Syst.* **119,** 10–21 (2013).

67. Seo, S. N. Modeling farmer adaptations to climate change in South America: a micro-behavioral economic perspective. *Environ. Ecol. Stat.* **23,** 1–21 (2016).

68. Bharwani, S. *et al.* Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **360,** 2183–94 (2005).

69. Soboll, A. *et al.* Integrated regional modelling and scenario development to evaluate future water demand under global change conditions. *Mitig. Adapt. Strateg. Glob. Chang.* **16,** 477–498 (2010).

70. Bone, C., Alessa, L., Altaweel, M., Kliskey, A. & Lammers, R. Assessing the impacts of local knowledge and technology on climate change vulnerability in remote communities. *Int. J. Environ. Res. Public Health* **8,** 733–61 (2011).

71. Ziervogel, G., Bithell, M., Washington, R. & Downing, T. Agent-based social simulation: a method for assessing the impact of seasonal climate forecast applications among smallholder farmers. *Agric. Syst.* **83,** 1–26 (2005).

72. Meza, F. J. & Silva, D. Dynamic adaptation of maize and wheat production to climate change. *Clim. Change* **94,** 143–156 (2009).

73. Antle, J. M., Stoorvogel, J. J. & Valdivia, R. O. New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **369,** 20120280 (2014).

74. Walsh, S. J., Messina, J. P., Mena, C. F., Malanson, G. P. & Page, P. H. Complexity theory, spatial simulation models, and land use dynamics in the Northern Ecuadorian Amazon. *Geoforum* **39,** 867–878 (2008).

75. Badmos, B., Agodzo, S., Villamor, G. & Odai, S. An Approach for Simulating Soil Loss from an Agro-Ecosystem Using Multi-Agent Simulation: A Case Study for Semi-Arid Ghana. *Land* **4,** 607–626 (2015).

76. Joffre, O. M. *et al.* Combining participatory approaches and an agent-based model for better planning shrimp aquaculture. *Agric. Syst.* **141,** 149–159 (2015).

77. Bakker, M. *et al.* The feasibility of implementing an ecological network in The Netherlands under conditions of global change. *Landsc. Ecol.* **30,** 791–804 (2015).

78. Cheng, K., Fu, Q., Li, T., Jiang, Q. & Liu, W. Regional food security risk assessment under the coordinated development of water resources. *Nat. Hazards* **78,** 603–619 (2015).

79. Berger, T. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agric. Econ.* **25,** 245–260 (2001).

80. Rose, S. K. Integrated assessment modeling of climate change adaptation in forestry and pasture land use: A review. *Energy Econ.* **46,** 548–554 (2014).

81. Yousefpour, R. *et al.* Modelling of adaptation to climate change and decision-makers behaviours for the Veluwe forest area in the Netherlands. *For. Policy Econ.* **54,** 1–10 (2015).

82. Cheung, W. W. L. & Sumaila, U. R. Trade-offs between conservation and socio-economic objectives in managing a tropical marine ecosystem. *Ecol. Econ.* **66,** 193–210 (2008).

83. Adger, W. N. Social and ecological resilience: are they related? *Prog. Hum. Geogr.* **24,** 347–364 (2000).

84. Naughton-Treves, L., Holland, M. B. & Brandon, K. THE ROLE OF PROTECTED AREAS IN CONSERVING BIODIVERSITY AND SUSTAINING LOCAL LIVELIHOODS. *Annu. Rev. Environ. Resour.* **30,** 219–252 (2005).

85. Mazzega, P. *et al.* Critical multi-level governance issues of integrated modelling: An example of low-water management in the Adour-Garonne basin (France). *J. Hydrol.* **519,** 2515–2526 (2014).

86. Barthel, R. *et al.* An integrated modelling framework for simulating regional-scale actor responses to global change in the water domain. *Environ. Model. Softw.* **23,** 1095–1121 (2008).

87. Berger, T. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agric. Econ.* **25,** 245–260 (2001).

88. Angus, S., Parris, B. & Hassani Mahmooei, B. Climate change impacts and adaptation in Bangladesh: An agent-based approach. *18th World IMACS Congr. MODSIM09 Int. Congr. Model. Simul. (David Mayer Neil Gribble 13 July 2009 to 17 July 2009)* 2720–2726 (2009).

89. Berman, M., Nicolson, C., Kofinas, G., Tetlichi, J. & Martin, S. Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model. *Arctic* **57,** 401–414 (2004).

90. Deng, X., Liu, J., Lin, Y. & Shi, C. A framework for the land use change dynamics model compatible with RCMs. *Adv. Meteorol.* Article ID 658941 (2013).

91. Seo, S. N. Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio diversification in African agriculture. *Food Policy* **35,** 32–40 (2010).

92. Belem, M., Manlay, R. J., Müller, J. P. & Chotte, J. L. CaTMAS: A multi-agent model for simulating the dynamics of carbon resources of West African villages. *Ecol. Modell.* **222,** 3651–3661 (2011).

93. Arneth, A., Brown, C. & Rounsevell, M. D. A. Global models of human decision-making for land-based mitigation and adaptation assessment. *Nat. Clim. Chang.* **4,** 550–557 (2014).

94. Macy, M. W. & Willer, R. From Factors to Factors: Computational Sociology and Agent-Based Modeling. *Annu. Rev. Sociol.* **28,** 143–166 (2002).

95. Jensen, T., Holtz, G. & Chappin, É. J. L. Agent-based assessment framework for behavior-changing feedback devices: Spreading of devices and heating behavior. *Technol. Forecast. Soc. Change* **98,** 105–119 (2015).

96. Happe, K., Kellerman, K. & Balmann, A. Agent-based Analysis of Agricultural Policies: an Illustration of the Agricultural Policy Simulator AgriPoliS, its Adaptation and Behavior. *Ecol. Soc.* **11,** (2006).

97. Sultana, F. Water, technology, and development: transformations of development technonatures in changing waterscapes. *Environ. Plan. D Soc. Sp.* **31,** 337–353 (2013).

98. Appel, F., Ostermeyer, A., Balmann, A. & Larsen, K. *Advances in Social Computing*. *Advances in Social Computing* **6007,** (Springer Berlin Heidelberg, 2010).

99. Berger, T. & Troost, C. Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. *J. Agric. Econ.* **65,** 323–348 (2014).

100. Flores, L. A., Martínez, L. I., Ferrer, C. M., Gallego, V. P. & Bermejo, A. S. A spatial high-resolution model of the dynamics of agricultural land use. *Agric. Econ.* **38,** 233–245 (2008).

101. Soman, S., Misgna, G., Kraft, S. E., Lant, C. & Beaulieu, J. R. An Agent-Based Model of Multifunctional Agricultural Landscape Using Genetic Algorithms. *2008 Annu. Meet. July 27-29, 2008, Orlando, Florida* (2008).

102. Oreskes, N., Shrader-Frechette, K. & Belitz, K. Verification, validation, and confirmation of numerical models in the Earth sciences. *Science* **263,** 641–6 (1994).

103. Windrum, P., Fagiolo, G. & Moneta, A. Empirical Validation of Agent-Based Models: Alternatives and Prospects. (2007).

104. van Vliet, J. *et al.* Advancing land-use modeling requires new data to understand and represent human decision making. *Rev.*

105. van Vliet, J. *et al.* A review of current calibration and validation practices in land-change modeling. *Environ. Model. Softw.* **82,** 174–182 (2016).

106. Dearing, J. A., Battarbee, R. W., Dikau, R., Larocque, I. & Oldfield, F. Human–environment interactions: towards synthesis and simulation. *Reg. Environ. Chang.* **6,** 115–123 (2006).

107. Bakker, M. M., Alam, S. J., van Dijk, J. & Rounsevell, M. D. A. Land-use change arising from rural land exchange: an agent-based simulation model. *Landsc. Ecol.* **30,** 273–286 (2014).

108. Brown, J. D. Prospects for the open treatment of uncertainty in environmental research. *Prog. Phys. Geogr.* **34,** 75–100 (2010).

109. Wegener, M. From Macro to Micro—How Much Micro is too Much? *Transp. Rev.* **31,** 161–177 (2011).

110. Sjølie, H. K., Latta, G. S., Trømborg, E., Bolkesjø, T. F. & Solberg, B. An assessment of forest sector modeling approaches: conceptual differences and quantitative comparison. *Scand. J. For. Res.* **30,** 60–72 (2015).

111. Nelson, G. C. *et al.* Agriculture and climate change in global scenarios: why don't the models agree. *Agric. Econ.* **45,** 85–101 (2014).

112. Parker, W. S. Ensemble modeling, uncertainty and robust predictions. *Wiley Interdiscip. Rev. Clim. Chang.* **4,** 213–223 (2013).

113. Conte, R. & Paolucci, M. On agent-based modeling and computational social science. *Front. Psychol.* **5,** 668 (2014).

114. Antunes, L. & Coelho, H. On how to conduct experimental research with self-motivated agents. *Regul. Agent-Based Soc. Syst.* **2934,** 31–47 (2004).

115. Crane, T. Of models and meanings: cultural resilience in social-ecological systems. *Ecol. Soc.* (2010).

116. Epstein, J. M. Why Model? (2008).

117. Verburg, P. H. *et al.* Methods and approaches to modelling the Anthropocene. *Glob. Environ. Chang.* (2015). doi:10.1016/j.gloenvcha.2015.08.007

118. Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G. & Gotts, N. M. Agent-based land-use models: a review of applications. *Landsc. Ecol.* **22,** 1447–1459 (2007).

119. Brown, C., Holzhauer, S., Metzger, M. J., Paterson, J. S. & Rounsevell, M. Land managers' behaviours modulate pathways to visions of future land systems. *Reg. Environ. Chang.* 1–15 (2016). doi:10.1007/s10113-016-0999-y

120. Magliocca, N. Model-Based Synthesis of Locally Contingent Responses to Global Market Signals. *Land* **4,** 807–841 (2015).

121. Lambin, E. F. & Geist, H. *Land-use and Land-cover Change: Local Processes and Global Impacts (Google eBook)*. (Springer, 2006).

122. Filatova, T., Polhill, J. G. & van Ewijk, S. Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. *Environ. Model. Softw.* **75,** 333–347 (2016).

123. Whitfield, S. & Reed, M. S. Participatory environmental assessment in drylands: Introducing a new approach. *J. Arid Environ.* **77,** 1–10 (2012).

124. Filatova, T., Verburg, P. H., Parker, D. C. & Stannard, C. A. Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environ. Model. Softw.* **null,** (2013).

125. Adger, W. N. *et al.* Are there social limits to adaptation to climate change? *Clim. Change* **93,** 335–354 (2008).

126. Flato, G. M. Earth system models: an overview. *Wiley Interdiscip. Rev. Clim. Chang.* **2,** 783–800

(2011).

127. Harris, R. M. B. *et al.* Climate projections for ecologists. *Wiley Interdiscip. Rev. Clim. Chang.* **5,** 621–637 (2014).

128. Lobianco, A. & Esposti, R. The Regional Multi-Agent Simulator (RegMAS): An open-source spatially explicit model to assess the impact of agricultural policies. *Comput. Electron. Agric.* **72,** 14–26 (2010).

129. Weaver, C. P. *et al.* Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdiscip. Rev. Clim. Chang.* **4,** 39–60 (2013).

130. Antle, J. M., Capalbo, S. M., Mooney, S., Elliott, E. T. & Paustian, K. H. Economic Analysis Of Agricultural Soil Carbon Sequestration: An Integrated Assessment Approach. *J. Agric. Resour. Econ.* **26,** (2001).

Figure captions

Figure 1: Modelled behaviour by sector. The number of models that include each form of behaviour is shown, so that one model may be included several times across the categories; this also means that cross-sectoral models contribute to more than one sector. Economic and individual behaviour does not include non-economic factors or social processes. Other categories may or may not be based on economic factors, but include distinct decision-making mechanisms.

Figure 2: Forms of validation or evaluation adopted by reviewed models

Figure 3: Geographical extent of models reviewed

Tables

First author & reference	Adaptation/ mitigation	Sector	Modelled behaviour	Decision-making	Perception of climate change	Model type
Alexander[47]	Adaptation	Agriculture	Diffusion, learning	Crop choice and investment in biomass power plant	Indirect (ES) impacts	ABM
Angus[88]	Adaptation	Agriculture, urban		migration, food consumption	Via market	ABM
Antle[130]	Adaptation	Agriculture		Adoption of different agricultural practice		IBM
Arnold[36]	Adaptation	Agriculture		Crop choice, investments, labour, saving/financing	Via institutions	ABM
Badmos[75]	Adaptation	Agriculture		Choice of crop system	Via institutions	Microsimulation
Bakker[107]		Agriculture		Buying & selling rural land		ABM
Barthel[86]	Adaptation	Cross-sectoral	Diffusion, social network, learning	Choices about water usage	Via market & institutions	ABM
Belem[92]		Agriculture		Crop choice, inputs (fertiliser), migration	Direct impacts	Microsimulation
Bell[50]	Mitigation	Agriculture, Forestry	Social network	Land use (e.g. de/re-forestation) and buying/selling of land	Indirect (ES) impacts	ABM
Berger[87]	Adaptation	Agriculture	Diffusion, social network	Investment, irrigation, crop type and technology, innovation adoption, persistence/abandonment		Microsimulation
Berger[99]		Agriculture	Diffusion, social network, learning	Crop selection, investments.		ABM
Berman[89]	Adaptation			Form households, harvest and hunt, share resources, look for jobs, migration	Indirect (ES) impacts, via institutions	ABM
Bharwani[68]	Adaptation	Agriculture	Learning		Indirect (ES) impacts, via market	ABM
Bone[70]			Diffusion, learning	Decisions are scenario-dependent.	Direct impacts, via institutions	ABM
Brown[49]	Mitigation	Agriculture	Diffusion	Adoption of bioenergy crops (forgoing profit)	Via institutions	ABM
Cheng[78]	Adaptation	Agriculture		Optimisation of water resource usage		ABM
Deng[90]	Mitigation, adaptation	General		Generic land use decision, based on decisions of similar 'households'	Direct impacts, via market	ABM
Dyer[46]	Mitigation	Forestry		Primarily whether to engage in subsidised reforestation scheme.	Via market & institutions	ABM
Ferreira[55]	Mitigation, adaptation	Agriculture, forestry		Land use/cover transitions	Via institutions	Microsimulation
Gimona[65]	Adaptation	Agriculture, forestry, conservation		Intensification/extensification based on climate suitability and policy interventions	Indirect (ES) impacts	ABM

Hannah[62]	Adaptation	Forestry		Harvesting & replanting	Indirect (ES) impacts, via market	
Jiang[52]	Mitigation	Agriculture		Decisions affecting cost and value of production		
Joffre[76]	Adaptation	Agriculture, forestry, coastal (mangroves)	Diffusion	Intensity of production	Direct, via institutions	ABM
Kerr[56]	Mitigation, adaptation	Agriculture, Forestry	Diffusion	Land use (land clearance, crop choice).	Direct impacts, via market & institutions	Microsimulation
Liu[61]	Adaptation	Agriculture		Technical options to maintain grazing suitability.		ABM
Malanson[57]	Adaptation	Agriculture		Crop selection	Indirect (ES) impacts	ABM
Matthews[53]	Mitigation	Agriculture	Social network, learning	Decisions about abstract land uses, made on basis of neighbours' land uses and strategies.		ABM
Mazzega[85]	Adaptation	Agriculture		crop allocation, irrigation, reservoir & water resource management.	Direct impacts, via institutions	Multi-agent system
Meza[72]	Adaptation	Agriculture	Learning	Adjustments in management (timing etc.) for specific crops	Indirect (ES) impacts	Microsimulation
Morgan[51]	Mitigation	Agriculture, forestry	Social network, learning	Selection of land based activity	Via market	ABM
Murray-Rust[64]	Adaptation	Agriculture, forestry		Whether to change/abandon land use		ABM
O'Connell[59]	Adaptation	Agriculture - flooding		Proposed model		ABM
Putra[60]	Adaptation	Urban, coastal	Diffusion	House purchase, modification and sale	Direct impacts, via market & institutions	ABM
Rammer[63]	Adaptation	Forestry	Diffusion	Forest management strategy and practices	Direct & indirect (ES) impacts	ABM
Salvini[54]	Mitigation, adaptation	Agriculture, forestry		Choice of agricultural management, deforestation	Direct impacts, via institutions	ABM
Scheffran[48]	Mitigation	Agriculture, forestry		Crop selection		ABM
Seo[67]	Adaptation	Agriculture		Choice of agricultural systems	Via institutions	Microsimulation
Soboll[69]	Adaptation	Urban	Diffusion	Water usage; quantities, adoption of new technologies	Direct & indirect impacts, via market & institutions	Microsimulation
Soman[101]	Adaptation	Agriculture		Agents adapt strategies based on context		ABM
Troost[39]	Adaptation	Agriculture		Crop selection and management	Indirect (ES) impacts	ABM

van Oel[58]	Adaptation	Agriculture		Crop irrigation decisions	Indirect (ES) impacts	ABM
Yan[66]	Adaptation	Agriculture, urban	Learning	Changes in land cover, primary focus on urban expansion		ABM
Yousefpour[81]	Adaptation	Forestry	Learning	Forest management practice		Microsimulation
Zhang[37]	Adaptation	Agriculture, forestry, conservation	Diffusion, learning	Land use, whether to sell or buy land parcels	Direct impacts, via market & institutions	ABM
Ziervogel[71]	Adaptation	Agriculture	Diffusion, learning	Timing and nature of crop activities	Direct impacts, via institutions	ABM

Table 1: Overview of models reviewed. Entries are made in a column only where the relevant issue is modelled (e.g. rather than used to motivate the model). Behaviours refer to those discussed in the text, and do not include economic rationality. Model type is based on that given in publication, not independent assessment, and ABM refers to agent-based model. Only papers that present models of land-based sectors are included (several relevant discussion/review papers are not included).