Behavioural Models of Land Systems

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Behavioural Models of Land Systems (BeModeLS) is a joint working group between AIMES and the Global Land Programme that aims to support and build interdisciplinary collaboration across the scientific disciplines represented by these global research networks. The group welcomes a wide range of perspectives and members with interests in building any aspects of human behaviour (e.g. individual, collective, and organisational) in land systems models and its interactions with other land system processes.

Why do we need Behavioural Models?

Human activity influences Earth systems in myriad ways, from agricultural choices causing soil erosion and water chemistry imbalances, to forestry management decisions modifying carbon emissions and biodiversity, to energy policy designs that shape the progress of climate change mitigation actions. But representation of such influences in Earth System Models (ESMs) is currently limited to broad generalisations of activity, through use of scenarios of possible economic and societal trajectories. For example, the Shared Socioeconomic Pathways in the IPCC Sixth Assessment Report provide narratives of possible climate change mitigation and adaptation actions that have subsequently been quantified to explore likely biophysical responses in the Earth system, such as climate change (Riahi, et al. 2017). These scenarios are quite limited in the spatial differentiation of socio-economic outcomes (O'Neill et al. 2020) and because they are exogenous to ESMs they provide no scope for representing human-environment feedbacks or adaptation of human activity to changing conditions (Donges et al. 2020). Furthermore, such approaches - including the Integrated Assessment Models used to turn the qualitative narratives into quantitative values for input to other models - assume a specific model of economic theory in which human behaviour is narrowly defined as (perfectly) economically rational and maximising. And yet, empirical observations have frequently shown how human decision-making deviates from this perfectly economically rational model (Schlüter et al. 2017). Humans are inherently adaptable with the potential to respond to stimuli in far more creative and inventive ways than standard economic models allow for. The inability to represent the great diversity of human behaviours in ESMs is a shortcoming that limits our understanding of the range of possible global outcomes over the coming decades.

What are Behavioural Models, anyway?

A key aim of the Behavioural Models of Land Systems (BeModeLS)

Modeling Approaches	Description	Strength	Weakness	References
Agent-based models	Disaggregated representation of actions and interactions of individuated actors	Flexibility allows different aspects of behaviour to be examined (e.g. maximising vs 'satisficing')	Potentially great data demands and large number of parameters to estimate	Filatova et al. (2013), Dressler et al. (2019), Heppenstall et al. (2020)
System Dynamics	Aggregated representation of flows and stocks of resources	Enables clear focus on flows and feedbacks of energy, goods and information	Requires 'stocks and flows' approach which may constrain representation of behaviour	Warner et al. (2013), Berrio-Giraldo et al. (2021)
Bayesian belief networks	Graph-based representation of conditional dependencies between components	Probabilistic representation and potential for automated specification of network structure	Representation of spatial dependencies and interactions can be challenging	Landyut et al. (2013), Andriatsitohaina et al. 2020
Conceptual models	Formal description of a system, often in diagrammatic form, to aid communication and theorising	Forces pre-specification of elements to be modelled prior to data collection and analysis	Relies on other modelling approaches for analytical, quantitative or computational implementation	Alberti et al. (2011), Gaughan et al. (2019)

Table 1. Examples of behavioural modelling approaches used for investigating human activity in Earth systems.

working group is to support the development and use of models that represent and enable understanding of the diversity of human behaviour as it occurs within land systems and particularly the use, management, conservation and restoration of land. Behaviour is more than just 'activity'; it implies response to stimuli and action that relates to external drivers, motivations, constraints, and resources. Behaviour is spatially and temporally variable and depends on social, environmental and other contexts in which it is expressed. Importantly, behaviour also occurs across organisational levels (e.g. institutions vs individuals) and spatial scales, having effects right up from local to global extents. As a result, human behaviour can lead to outcomes in land systems (and elsewhere) that are, at least for periods of time, very far from economically optimal (Brown et al. 2019).

It makes sense that land systems research started with rational choice theory, as this is where much theorising and data collection was focused during the 20th century. But advances in the behavioural sciences (including behavioural economics) and simulation modelling have enabled the development of approaches such as agent-based modelling, in which varied behaviours (including bounded rationality, and evolutionary learning) are explicitly represented at the level of actors within the system (e.g. Filatova et al. 2013, Dressler et al. 2019, Heppenstall et al. 2020). This is not to say all behavioural models are agent-based, and in practice can take many forms including system dynamics (Warner et al. 2013, Berrio-Giraldo et al. 2021), Bayesian belief networks (Andriatsitohaina et al. 2020) and conceptual models (Gaughan et al. 2019), and could even be combined (Millington et al. 2017). Each approach has strengths and weaknesses (Table 1) and the choice will depend on the particular questions in hand. The key is that these newer modelling approaches seek representations of human behaviour and institutional

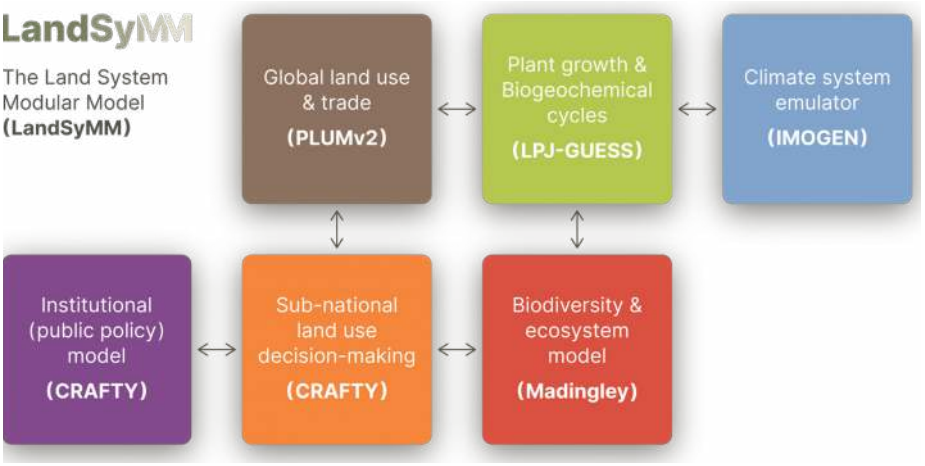

Fig. 1. LandSyMM loosely couples multiple process-based models, including the CRAFTY behavioural agent-based modelling platform, to represent multiple components of the Earth system. (Source: landsymm.earth).

processes that are an alternative to optimisation, and acknowledge and explore the heterogeneity in which land management decision-making and activities proceed.

So, what's the link to AIMES?

We expect that developing behavioural models of land systems across geographical scales and organisational levels will improve understanding of processes that are of direct concern to the goals of AIMES, particularly regarding feedbacks between human activities and components of the earth system. This also provides a direct link to the work of the Global Land Programme, another international network of Future Earth with which the BeModeLS group is affiliated. Land system scientists are now beginning to identify how behavioural models can be developed and employed at large spatial extents (e.g. continental; Brown et al 2019, Millington et al. 2021) and opportunities to link or directly couple large-scale behavioural models of land systems with earth system models are becoming more feasible, although not yet attempted. For example, Ford et al (2020) discuss the alternative possible approaches for outputs from a global agent-based model (ABM) of human fire use and management to be incorporated in a fire-enabled dynamic global vegetation model (DGVM). This might take the form of a loose coupling in which the ABM endogenously provides inputs by replacing existing estimates of anthropogenic fire ignitions (e.g. from population density) to better capture drivers of ignitions (e.g. socio-economic circumstances of actors), or a tighter coupling in which the ABM runs iteratively with the fire-enabled DGVM providing ignitions estimates and also receiving changes in simulated vegetation back to influence the next round of human fire ignitions.

Such tight coupling of feedbacks between human behaviour and Earth system processes might be a long-term endeavour, but in the shorter term looser coupling of models to better represent behaviour and to understand how existing scenarios of change can be improved is a key goal. For example, coupled models might provide improved representation of future socioeconomic pathways by incorporating scenario elements relating to social-ecological feedbacks or resource constraints across competing land use sectors. The Land System Modular Model (LandSyMM) provides an interesting example of this goal, providing the opportunity to couple spatially-explicit and process-based models such as CRAFTY (Brown et al. 2019), PLUMv2 (Henry et al. 2022) and Madingley (Harfoot et al. 2014) to investigate the impacts of combined and interacting changes from local to global scales (Figure 1). Understanding feedbacks is important given the adaptive nature of human behaviour within land

systems. For example, the capacity of land managers to respond to things like conservation policy instruments depends on their social, human, financial and physical capital (Lockwood et al. 2015), each of which may vary by socioeconomic scenario and according to local factors.

Where's all this going?

The goal of the BeModeLS working group is not primarily to incorporate human behaviour into ESMs but to support efforts to develop behavioural models of human activity within land systems and to couple them with other models, including ESMs, through improved understanding of the processes underlying human-environment interactions. Furthermore, it's important we emphasise that the BeModeLS working group is not seeking solely to support development of models operating at global extent, but also models at landscape and local scales as there is still much understanding to be gained here. Thus, the overall aim of the BeModeLS working group is to support the creation of the next generation of land system models that represent diverse human behaviour, agency, decision-making and institutional processes. The full list of our specific objectives can be found on our webpage.
In the medium term we aim to support the construction of a library of models and associated code to enable comparison and synthesis of approaches and mechanisms for modelling human behaviour in land systems. In the short term we aim to host an online workshop on 16 February 2023 to discuss and plan activities to achieve our objectives and we welcome you to join us. Even if you are not a modeller yourself, we welcome participants to suggest and discuss processes and dynamics we should prioritise and the types of experiments and comparisons we should commit our modelling to. Only an inclusive, active, diverse and cooperative community of social-ecological land scientists will be able to fully realise the potential of behavioural models to contribute to mitigating our current environmental crises. We are committed to developing just such a working group. □

References

Alberti, M., Asbjornsen, H., Baker, L. A., Brozović, N., Drinkwater, L. E., Drzyzga, S. A., ... & Urquhart, G. (2011). Research on coupled human and natural systems (CHANS): approach, challenges, and strategies. Bulletin of the Ecological Society of America. 10.1890/0012-9623-92.2.218

Andriatsitohaina, R.N.N., Celio, E., Llopis, J.C., Rabemananjara, Z.H., Ramamonjisoa, B.S., and Grêt-Regamey, A. (2020). Participatory Bayesian network modeling to understand driving factors of land-use change decisions: insights from two case studies in northeast Madagascar. Journal of Land Use Science 15, 69–90. 10.1080/1747423X.2020.1742810.

Berrio-Giraldo, L., Villegas-Palacio, C., and Arango-Aramburo, S. (2021). Understating complex interactions in socio-ecological systems using system dynamics: A case in the tropical Andes. Journal of Environmental Management 291, 112675. 10.1016/j.jenvman.2021.112675.

Brown, C., Alexander, P., Arneth, A., Holman, I., and Rounsevell, M. (2019). Achievement of Paris climate goals unlikely due to time lags in the land system. Nat. Clim. Chang. 9, 203–208. 10.1038/s41558-019-0400-5.

Donges, J.F., Heitzig, J., Barfuss, W., Wiedermann, M., Kassel, J.A., Kittel, T., Kolb, J.J., Kolster, T., Müller-Hansen, F., Otto, I.M., et al. (2020). Earth system modeling with endogenous and dynamic human societies: the copan:CORE open World–Earth modeling framework. Earth Syst. Dynam. 11, 395–413. 10.5194/esd-11-395-2020.

Dressler, G., Groeneveld, J., Buchmann, C.M., Guo, C., Hase, N., Thober, J., Frank, K., and Müller, B. (2019). Implications of behavioral change for the resilience of pastoral systems—Lessons from an agent-based model. Ecological Complexity 40, 100710. 10.1016/j.ecocom.2018.06.002.

Filatova, T., Verburg, P.H., Parker, D.C., and Stannard, C.A. (2013). Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environmental Modelling & Software 45, 1–7. 10.1016/j.envsoft.2013.03.017.

Ford, A.E.S., Harrison, S.P., Kountouris, Y., Millington, J.D.A., Mistry, J., Perkins, O., Rabin, S.S., Rein, G., Schreckenberg, K., Smith, C., et al. (2021). Modelling Human-Fire Interactions: Combining Alternative Perspectives and Approaches. Front. Environ. Sci. 9, 649835. 10.3389/fenvs.2021.649835.

Gaughan, A., Stevens, F., Pricope, N., Hartter, J., Cassidy, L., and Salerno, J. (2019). Operationalizing Vulnerability: Land System Dynamics in a Transfrontier Conservation Area. Land 8, 111. 10.3390/land8070111.

Harfoot, M.B.J., Newbold, T., Tittensor, D.P., Emmott, S., Hutton, J., Lyutsarev, V., Smith, M.J., Scharlemann, J.P.W., and Purves, D.W. (2014). Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model. PLoS Biol 12, e1001841. 10.1371/journal.pbio.1001841.

Henry, R.C., Arneth, A., Jung, M., Rabin, S.S., Rounsevell, M.D., Warren, F., and Alexander, P. (2022). Global and regional health and food security under strict conservation scenarios. Nat Sustain 5, 303–310. 10.1038/s41893-021-00844-x.

Heppenstall, A., Crooks, A., Malleson, N., Manley, E., Ge, J., and Batty, M. (2021). Future Developments in Geographical Agent-Based Models: Challenges and Opportunities. Geogr. Anal. 53, 76–91. 10.1111/gean.12267.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., & Goethals, P. L. (2013). A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software, 46, 1-11. 10.1016/j.envsoft.2013.03.011

Lockwood, M., Raymond, C.M., Oczkowski, E., and Morrison, M. (2015). Measuring the dimensions of adaptive capacity: a psychometric approach. E&S 20, art37. 10.5751/ES-07203-200137.

Millington, J. D., Xiong, H., Peterson, S., & Woods, J. (2017). Integrating modelling approaches for understanding telecoupling: Global food trade and local land use. Land, 6(3), 56. 10.3390/land6030056

Millington, J.D.A., Katerinchuk, V., Silva, R.F.B. da, Victoria, D. de C., and Batistella, M. (2021). Modelling drivers of Brazilian agricultural change in a telecoupled world. Environmental Modelling & Software 139, 105024. 10.1016/j.envsoft.2021.105024.

O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., ... & Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. Nature climate change, 10(12), 1074-1084. 10.1038/s41558-020-00952-0

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153–168. 10.1016/j.gloenvcha.2016.05.009.

Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M.A., McAllister, R.R.J., Müller, B., Orach, K., et al. (2017). A framework for mapping and comparing behavioural theories in models of social-ecological systems. Ecological Economics 131, 21–35. 10.1016/j.ecolecon.2016.08.008.

Warner, E., Inman, D., Kunstman, B., Bush, B., Vimmerstedt, L., Peterson, S., ... & Zhang, Y. (2013). Modeling biofuel expansion effects on land use change dynamics. Environmental Research Letters, 8(1), 015003. 10.1088/1748-9326/8/1/015003