



EEIST



**AGRICULTURE:
SUPPORTING SUSTAINABLE
AGRICULTURE INTENSIFICATION:
A SYSTEM-WIDE AGENT-BASED
MODELLING APPROACH**



This document presents only one of the modelling case studies in the ‘New economic models of energy innovation and transition: Addressing new questions and providing better answers’ report, produced by the EEIST project.

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About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are **UK**: University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, **India**: The Energy and Resources Institute, World Resources Institute, **China**: Beijing Normal University, Tsinghua University, Energy Research Institute, **Brazil**: Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) **EU**: Scuola Superiore di Studi Universitari e di Perfezionamento Sant’Anna.

Contributors

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CASE STUDY:

Supporting Sustainable Agriculture Intensification: A system-wide agent-based modelling approach

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Policy question: Should institutions support sustainable agricultural intensification, and which factors make such intervention more urgent?

Region: Global

Methods: Agent-based model

Key finding(s): (1) Institutions should promote and incentivise sustainable farming; (2) their protection and nurturing is particularly beneficial when done in the early stages of the simulation; (3) supporting policies can involve a mixture of tax-based and command-and-control instruments; (4) if supporting policies are introduced too late, the technological gap might become so large that it becomes impossible to avoid a lock-in scenario in unsustainable agricultural practices.

Engagement: This case study emerged from a long and close collaboration between research teams at the Institute of Economics, the Institute of Life Science and the Center of Plant Sciences at Scuola Superiore Sant'Anna. Topic, questions and parts of the modelling were closely debated during stakeholder meeting, including Brazilian government officials and representatives of the Brazilian Development Bank (BNDES). As such, outputs of the case study were co-produced closely with policy stakeholders.

Summary: The authors use an ABM to consider a number of policies in support of the productivity gap of sustainable farming. Specifically, the study presents the agriLOVE model, which is characterised by high level of uncertainty, reinforcing feedback loops modelling competitions between firms/farms, and heterogeneity.

Introduction

With the global population projected to increase steadily during the next century and soil degradation already affecting the cultivation of major crops worldwide,¹⁷⁰ agricultural systems are in need of finding sustainable intensification strategies quickly to ensure viable food security pathways.^{171 172 173 174} Supporting sustainable agriculture intensification has become a crucial need, as the agricultural sector is slowly eroding crucial environmental resources, contributing to dangerous crossing of environmental boundaries, and possibly activating positive/negative tipping points.¹⁷⁵ Here we investigate which factors might impede or foster such transition while ensuring food security, and the subsequent policy implications. More explicitly, from a policy perspective, this translates into the following question: should institutions support sustainable intensification, and which factors make such intervention more urgent?

Modelling approach

With respect to canonical Integrated Assessment Models (IAMs), ABMs can offer a valid alternative paradigm to investigate these issues. They are increasingly employed in the domain of agricultural economics, because of the inherent complexity of socio-environment interactions.^{176 177 178 179} In addition, they can easily accommodate realistic representations of boundedly rational decision making, complex-social interactions among different actors (e.g., networks or property structures), the presence of self-reinforcing feedback loops, genuine and built-in path dependency, the integration of biophysical sub-models, and an explicit representation of non-trivial spatially based interactions.

To investigate which factors might help or impede transition to sustainable agriculture, we employ the agriLOVE model.¹⁸⁰ Unlike other agricultural ABM models, a key feature of agriLOVE is to

explicitly model endogenous technical change in agriculture, thus allowing for the investigation of different, path-dependent trajectories of evolution of technical paradigms, their uptake by agents and their aggregate outcome – in terms of food security and depletion of natural resources. As such, the model constitutes a testbed for alternative policy, institutional and environmental scenarios and the assessment of their relative risks and opportunities. Our approach is in line with the Risk-opportunity analysis (ROA) framework.¹⁸¹ In particular, the model embeds core concepts of the ROA approach, including i) radical uncertainty (agents do not know the distribution of the possible states of the world, whose support cannot be known a priori), ii) path-dependency, where endogenous scenarios emerging in the model diverge from each other, and crucially depend on actions taken and states of the system observed in the past, ii) persistent disequilibrium, since the model economy has no super-imposed tendency to reach an equilibrium, but gravitates around stable trajectories as the result of continued coordination efforts among highly heterogeneous actors and iv) disproportionality of cause and effect, where small perturbations to the system can lead to drastically different trajectories via path-dependence and highly non-linear dynamics. At the current stage the model is not parameterised to a specific area but is instead representative of macro-regions mainly characterised by smallholder farming.

The model is characterised by a collection of agent farms, operating on a spatially explicit grid, representing arable lands as well as natural resources – virgin lands or forestry (Figure 58C). Each farm combines labour and land to produce a homogeneous bundle of food. Farms are owned by firms, which collect the output produced and sell it on a centralised, monopsonistic market. Market outcomes, in turn, influence future decisions carried out by agent farms/firms. Given the strong technological and environmental uncertainty,

¹⁷⁰ Ray, D.K. et al. (2012). Recent Patterns of Crop Yield Growth and Stagnation. *Nature communications*, 3: 1293.

¹⁷¹ Rockström, J. et al. (2017). Sustainable Intensification of Agriculture for Human Prosperity and Global Sustainability. *Ambio*, 46(1): 4–17.

¹⁷² Ramankutty, N. et al. (2018). Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology* 69: 789–815.

¹⁷³ Tilman, D. et al. (2002). Agricultural Sustainability and Intensive Production Practices. *Nature*, 418(6898): 671–677.

¹⁷⁴ Howden, S.M. et al. (2007). Adapting Agriculture to Climate Change. *Proceedings of the National Academy of Sciences*, 104(50): 19691–19696.

¹⁷⁵ Steffen, W. et al. (2015). Planetary Boundaries: Guiding human development on a changing planet. *Science*, 347(6223): 1259855.

¹⁷⁶ Filatova, T. et al. (2013). Spatial Agent-Based Models for Socio-Ecological Systems: Challenges and Prospects. *Environmental Modelling & Software* 45: 1–7.

¹⁷⁷ Berger, T. (2001). Agent-based Spatial Models Applied to Agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics* 25(2-3): 245–260.

¹⁷⁸ Bert, F. E. et al. (2011). An Agent Based Model to Simulate Structural and Land use Changes in Agricultural Systems of the Argentine Pampas. *Ecological Modelling*, 222(19): 3486–3499.

¹⁷⁹ Berger, T. and Troost, C. (2014). Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. *Journal of Agricultural Economics*, 65(2): 323–348.

¹⁸⁰ Coronese, M. et al. (Forthcoming). AgriLove: Agriculture, Land-Use and Technical Change in an Evolutionary, Agent-Based Model. *Ecological Economics*.

¹⁸¹ Mercure, J-F. et al. (2021). Risk-Opportunity Analysis for Transformative Policy Design and Appraisal. *Global Environmental Change*, 70: 102359.

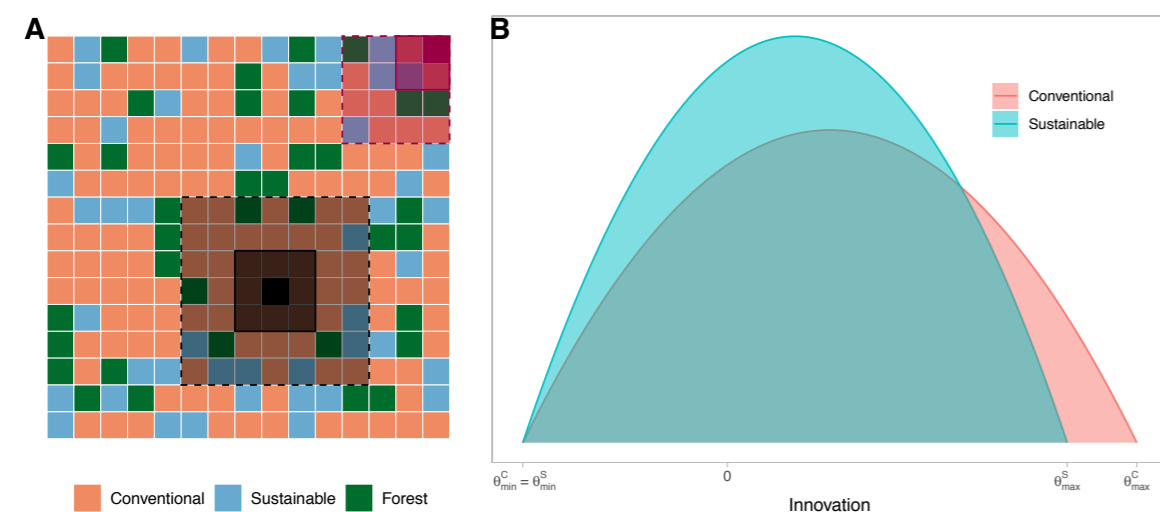
agents learn and adaptively employ heuristics which guide their decisions on engaging in innovation and imitation activities – for instance, they dynamically adjust the amount of resources devoted to these costly activities depending on their cash flow, and actively select best-performers among neighbouring farms to imitate. They also hire workers, acquire new farms, deforest virgin areas and abandon unproductive lands, adaptively trying to adjust production in order to meet perceived, possibly inaccurate, future levels of demand. Innovation and imitation activities capture, in an evolutionary fashion, the salient aspects of the costly process of search for productivity-enhancing new discoveries, including dynamic learning and knowledge diffusion patterns along distinct dimensions (technological proximity, spatial proximity and network effects).

We focus here in particular on modelling the dichotomy between conventional vs sustainable agricultural techniques – as commonly taxonomised in the literature¹⁸² – and investigate the dynamic diffusion and learning patterns among these different technological trajectories. Typically, conventional farming refers to those practices which use synthetic chemicals and fertilisers to maximise the yield of a particular set of crops, often genetically modified and characterised by mono-cropping. These

methods require a significant amount of chemical and energy input and may weaken the ecology of a landscape.¹⁸³ Sustainable farming is instead a broad definition, usually identifying all those agricultural paradigms which reintegrates soil nutrients during the production process. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the intensive use of chemical inputs.¹⁸⁴ It often triggers positive externalities for the environment as a whole.¹⁸⁵

In order to do so, we assume that conventional techniques tend to achieve more productivity-enhancing innovation discoveries than sustainable ones (Figure 58B) – reflecting their historically higher yields – and that conventional techniques can result in greater exploitation of available natural resources such as forests. However, prolonged usage of conventional techniques will lead to a loss of productivity due to soil degradation, possibly leading to stagnating yields, observed in the real world. On the other hand, sustainable techniques have less growth potential, but they do not lead to soil depletion. Agents dynamically choose which technology to employ, basing their decision on the perceived productivity of a given technological option in neighbouring areas (Figure 58A).

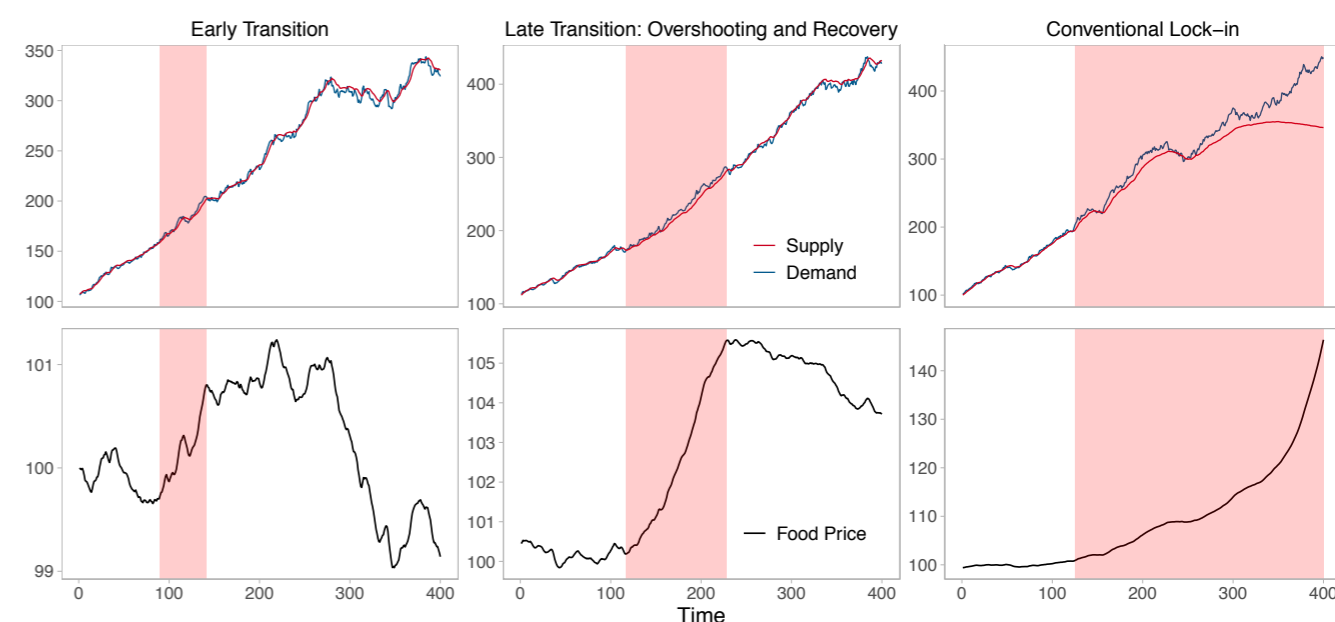
Figure 57: Panel A: An example of farms with different observational horizons (and thus different information sets) from distinct locations on the model spatial grid, when evaluating relative performances of different technological options. **Panel B:** Distribution of innovation outcomes for conventional and sustainable farming. X-axis represents gains in productivity, y-axis represents their relative probability. Conventional farming displays a larger set of innovation opportunities, leading to higher innovation potential and yields (without considering soil degradation).



Current technological choices of agents influence not only contemporaneous food prices and food security, but dynamically shape the trajectories of development of distinct technical paradigms within the agriculture sector, through feedback loops in innovation expenditures and imitation/diffusion patterns. As such, the system can evolve toward a sustainable transition, a conventional lock-in (with sudden collapse of yields and food security) or a

delayed transition (over-shooting), as conventional farmers resort to augmented labour force or deforestation to contrast stagnating yields (Figure 58). Both lock-ins and delayed transition are highly harmful in terms of food security, food prices and depletion of natural resources. The probability of realisation of these endogenous scenarios crucially depends on several factors.

Figure 58: Three different single runs of the model, exemplifying the main types of dynamics observed in the model: rapid transition to sustainable farming, overshooting (or late transition) and conventional lock-in. For each run, the distance between total demand and supply and the food price dynamics are shown. X-axis represents time steps in model simulation, y-axis represents changes with respect to initial values (set equal to 100). Red areas correspond to periods of insufficient food.



¹⁸² Saifi, B. and Drake, L. (2008). A Coevolutionary Model for Promoting Agricultural Sustainability. *Ecological Economics*, 65(1): 24-34

¹⁸³ Schrama, M. et al. (2018). Crop Yield Gap and Stability in Organic and Conventional Farming Systems. *Agriculture, Ecosystems & Environment* 256: 123-130.

¹⁸⁴ Gomiero, T. et al. (2011). Environmental Impact of Different Agricultural Management Practices: Conventional Vs. Organic Agriculture. *Critical Reviews In Plant Sciences*, 30(1-2): 95-124

¹⁸⁵ Rockström, J. et al. (2017). Sustainable Intensification of Agriculture for Human Prosperity and Global Sustainability. *Ambio*, 46(1): 4-17.

Results

Overall, our analysis shows that the agricultural system, if left unsupported by appropriate policies, has a small capacity of favouring sustainable transition, because of mis-aligned incentives and coordination failures. For instance, short-run approaches to increasing productivity, such as the depletion of natural resources or soil over-exploitation – which create long-run problems – typically grant a competitive advantage to the

farms that use them. This, via path dependence, leads to higher market shares for farms employing conventional techniques, which in turn further delays the collective learning needed for the sustainable trajectory. Figure 59 shows that the likelihood of transition rapidly deteriorates along with switching intensity (a measure of the willingness of farms to rapidly change their technology) and with available information, indicating a fragile and precarious market position of sustainable farmers.

Figure 59: Heat maps for different values of switching intensity (how much agents weigh perceived differences in performance between conventional and sustainable when choosing their agricultural regime) and radius of observation (see Figure 57A). Transition likelihood is defined as the share of Monte Carlo model runs with the final share of sustainable farms greater than 90 per cent. Transition end date indicates the percentage of simulation length at which the transition ends, thus providing a measure of transition speed. Food scarcity is defined as the share of time steps in which the food supply falls short of food demand by more than 5 per cent. Remaining forests are expressed as percentage of the initial stock of forestry. Food scarcity and remaining forests are Monte Carlo means. 50 Monte Carlo replications.

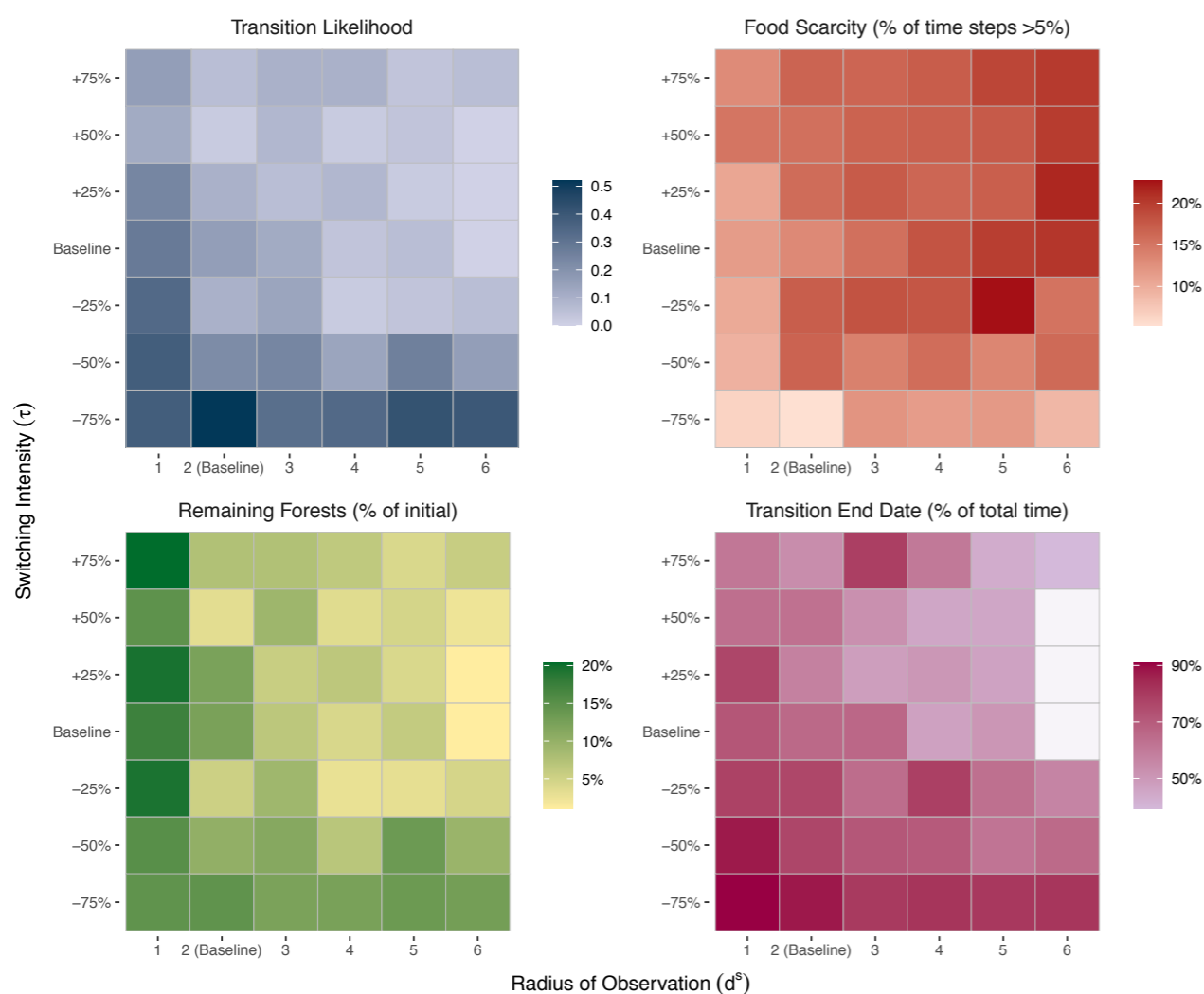
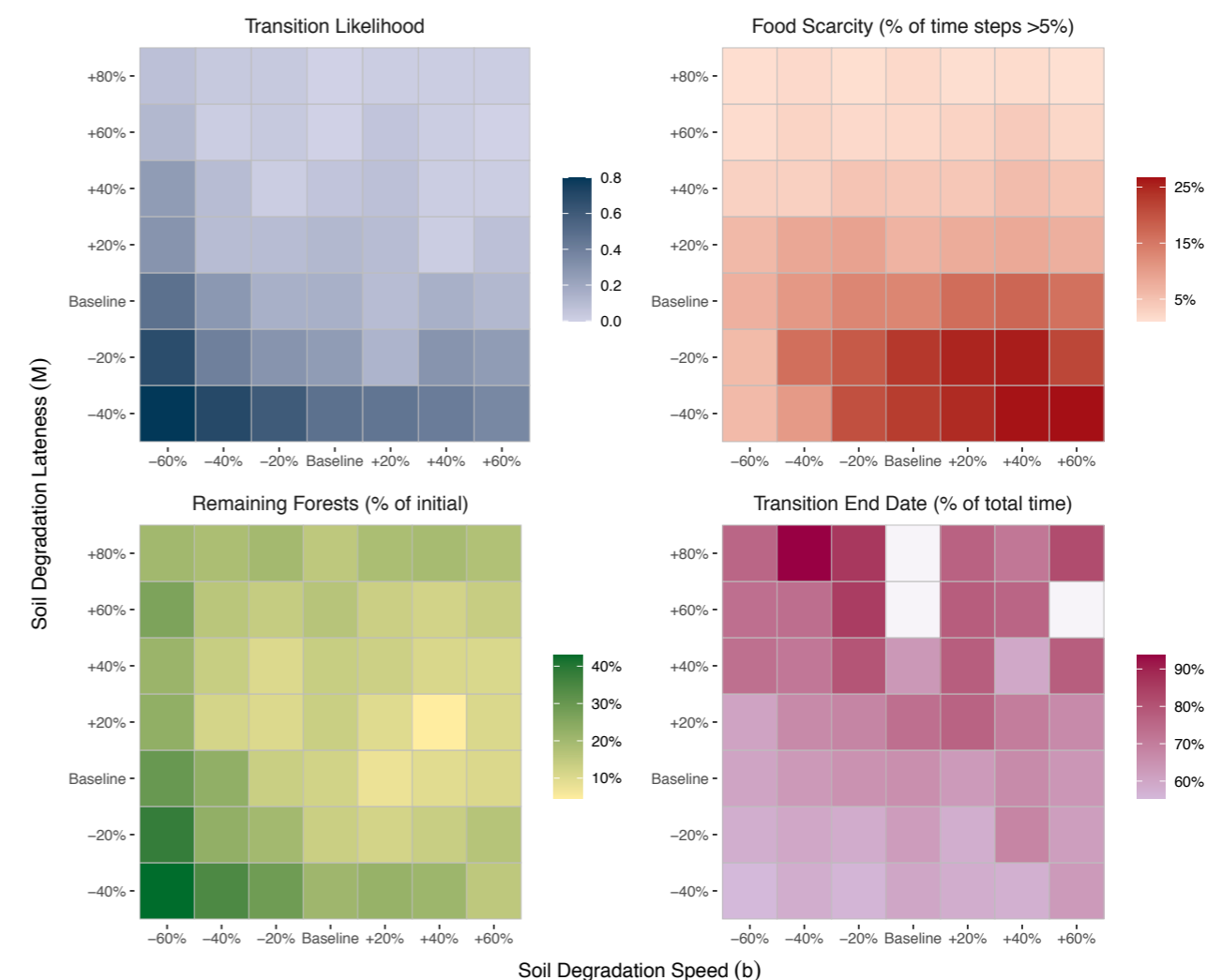


Figure 60 instead shows that agricultural systems perform particularly poorly in terms of favouring sustainable transition when facing rapid and delayed soil degradation phenomena.

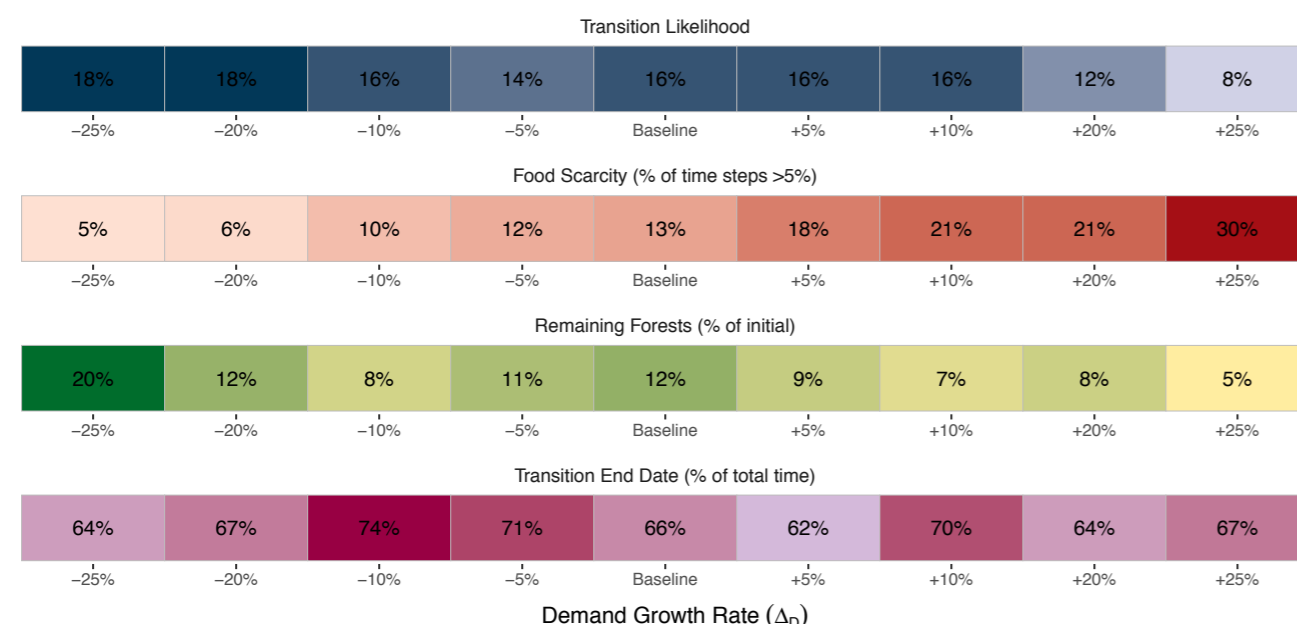
Figure 60: Heat-maps for different values of soil degradation speed (how fast maximum soil damage is reached once the first signs of slowing productivity appear) and lateness (how late in time the first signs of damaging effects appear with prolonged usage). Transition likelihood is defined as the share of Monte Carlo model runs with the final share of sustainable farms greater than 90 per cent. Transition end date indicates the percentage of simulation length at which the likelihood ends, thus providing a measure of transition speed. Food scarcity is defined as the share of time steps in which the food supply falls short of food demand by more than 5 per cent. Remaining forests are expressed as percentage of the initial stock of forestry. Food scarcity and remaining forests are Monte Carlo means. 50 Monte Carlo replications.



This finding underlines that market's feedbacks might be insufficient to favour a timely and successful transition when dealing with complex, delayed and not easily measurable environmental feedbacks on productivity and yields. Overall, the probability of

transitioning is negatively affected by food demand growth (Figure 61), posing serious concerns about food-security under scenarios of rapid population growth.

Figure 61: Heat maps for different rates of growth of food demand. Transition likelihood is defined as the share of Monte Carlo model runs with the final share of sustainable farms greater than 90 per cent. Transition end date indicates the percentage of simulation length at which the likelihood ends, thus providing a measure of transition speed. Food scarcity is defined as the share of time steps in which the food supply falls short of food demand by more than 5 per cent. Remaining forests are expressed as percentage of the initial stock of forestry. Food scarcity and remaining forests are Monte Carlo means. 50 Monte Carlo replications.



Lastly, the topological structure of sustainable diffusion (and its interplay with available natural resources) matters too. As shown in Figure 62A and 62B, having sustainable farmers clustered (which might favour local imitation but slow down their diffusion via local technology uptake) does not

significantly affect transition likelihood. However, clustered natural resources (and thus less easily exploitable) do marginally favour sustainable transition (Figure 62C), by impeding conventional farmers to resort to deforestation as a short-run fix to descending yields.

Figure 62: Heat maps for different initial spatial distributions of conventional and sustainable farms. Transition likelihood is defined as the share of Monte Carlo model runs with the final share of sustainable farms greater than 90 per cent. Transition end date indicates the percentage of simulation length at which the likelihood ends, thus providing a measure of transition speed. Food scarcity is defined as the share of time steps in which the food supply falls short of food demand by more than 5 per cent. Remaining forests are expressed as percentage of the initial stock of forestry. Food scarcity and remaining forests are Monte Carlo means. 50 Monte Carlo replications.

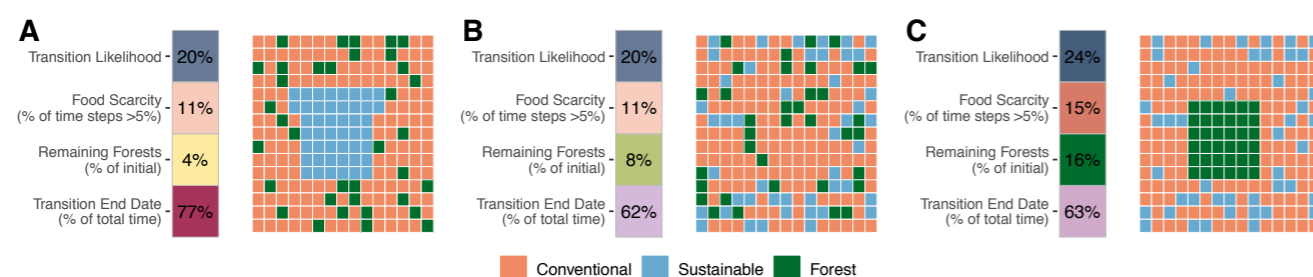
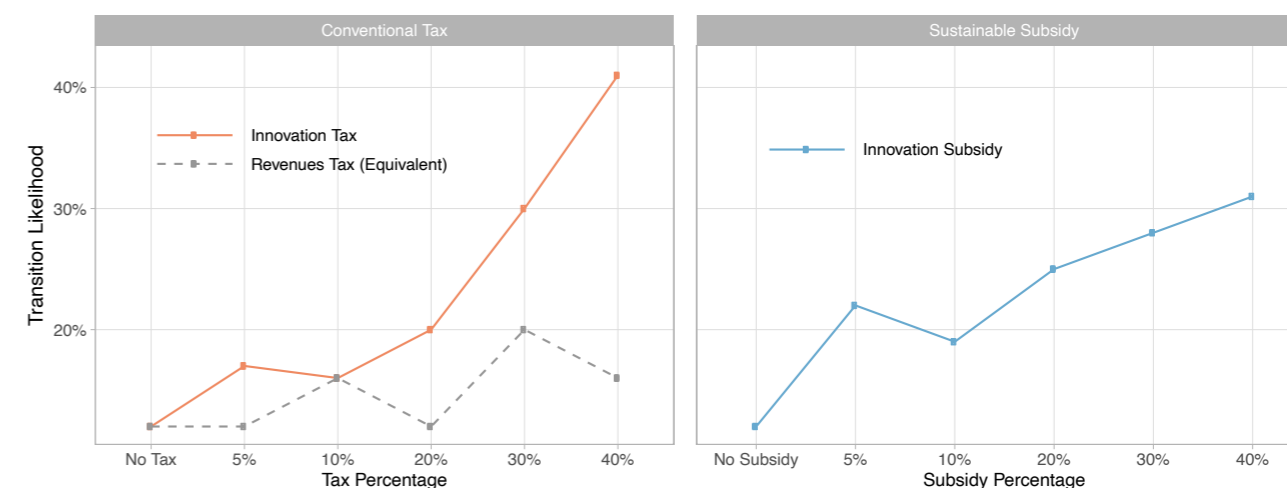


Figure 63: Transition likelihoods for different policies. Innovation subsidies/taxes are percentages of previous period innovation expenditures carried out by sustainable/conventional farms. Revenues tax amount is equal to the monetary equivalent of the innovation tax. Transition likelihood is defined as the share of Monte Carlo model runs with the final share of sustainable farms greater than 90 per cent. Transition end date indicates the percentage of simulation length at which the likelihood ends, thus providing a measure of transition speed. 100 Monte Carlo replications.



Policy implications and conclusion

What emerges from our analysis is that, not only should institutions promote and incentivise sustainable farming, but their protection and nurturing is particularly beneficial when done in the early stages of the simulation. Supporting policies can involve a mixture of tax-based and regulatory instruments.

On the demand side, policies aimed at reducing food waste could certainly play a role in diminishing food scarcity, although they are bound to become progressively less effective for closing the gap between supply and demand in scenarios with high population growth. Spatial dynamics matter too: encouraging clustered communities can help mutual imitation and dynamic learning, but should be accompanied by policies aimed at speeding up the velocity of transition (e.g. by imposing a minimum percentage of terrains to be cultivated with sustainable techniques within a given date).

Regulatory policies can be highly effective (e.g. simply prohibiting deforestation), but would nonetheless result in major short-run food shortages if not coupled with timely policies to reduce the productivity gap between sustainable and conventional techniques. Tax-based policies can be represented by a combination of taxes on conventional farms and incentives toward sustainable ones. To maximise

their impact in terms of transition likelihood – and minimise their distortive impact – they should, however, be explicitly targeted at increasing the resources that farms invest in innovation and imitation of sustainable agriculture activities.

Figure 63 shows the effects of these two different policies. Subsidies to sustainable farms are already effective at increasing the probability of transition with relatively low amounts, although their effectiveness increases less than linearly, along with the subsidy amount. This indicates that subsidies can represent a powerful tool to boost sustainable intensification, although with limited effectiveness due to the structural gap between conventional and sustainable techniques (see Figure 57B). On the other hand, when taxing conventional farmers, transition likelihood increases more than linearly with tax severity. Taxes are however highly ineffective if their amount is not substantial, or if they are not directly targeted at innovation expenditures (see Revenues Tax in Figure 63).

In other words, centralised policies aimed at closing the productivity gap between sustainable and conventional techniques are not only needed, but are time-dependent, with rapidly closing windows of opportunity. If supporting policies are introduced too late, the technological gap might become so large that it becomes impossible to avoid a lock-in scenario in unsustainable agricultural practices.

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Economics of Energy Innovation and System Transition

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