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Understanding Resilience in Food Systems: Shocks, Policies, and Reversals

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Understanding resilience in food systems: Shocks, Policies, and Reversals

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Abstract (Nature style)

The food system of the future must be resilient to unprecedented shocks. The complex food system will respond in many ways - brittle parts may break, others may adapt or even benefit. Multiple and compounding shocks may irreversibly tip the system into new, stable but degraded states. Food policy, and the emergent configurations of markets and supply chains that it drives, must at minimum avoid making food systems more fragile, but ideally should account for and even enhance resilience. ‘Resilience’ is an inherently complex property of any system, emerging from interconnectivity, covering the capacity of a system to withstand (robustness), recover from (recovery), and respond to (adaptation) shocks. To appropriately capture the distributional and dynamic processes fundamental to food system resilience requires a complex systems approach. Here we show that the different shocks expected to impact food systems produce different patterns of resilience (e.g., strong recovery but weak robustness) across SDG relevant outcomes and farming populations. We shed new light on how resilience (fails to) emerges in current food systems in the face of repeated shocks, with analysis revealing different resilience strengths and weaknesses, depending on shock type (e.g., adaptation to, but poor recovery from, general system shocks). Moreover, our results provide novel insights into the impact of policies as shocks, wherein we demonstrate not only the dangers of lacking commitment mechanisms to ambitious policies, but also the dangers of insufficient ambition. Our findings emphasise the importance of tailoring food system policies to the realities of local expected shock patterns. Without approaches that can capture the emergent properties of resilience, policy design is likely to inadequately address where current food systems are vulnerable (e.g., who will be worst affected, and in what manner?), undermining long-term success and risking harmful compounding cycles of policy reversals and further uncertainty.

Abstract Alternate

The food system of the future must be resilient to unprecedented supply and demand shocks. Some will be short-lived and sporadic (e.g., droughts, price spikes and even policy change), others will be sustained (e.g., environmental degradation or changing consumer preferences). The complex food system will respond in many ways - brittle parts may break, others may adapt or even benefit. Multiple and compounding shocks may irreversibly tip the system into new, stable but degraded states. Food policy, and the emergent configurations of markets and supply chains that it drives, must at minimum avoid making food systems more fragile. Policies must be based on a sound understanding of the trade-offs between resilience, efficiency, and productivity. ‘Resilience’ is an inherently complex property of any system, driven by interconnectivity. It covers the capacity of a system to withstand (robustness), recover from (recovery), and respond to (adaptation) shocks. These are dynamic responses that vary across systems and actors. Resilience is an *emergent* phenomenon - not easily predictable even by experts.

To appropriately capture the distributional and dynamic processes fundamental to food system resilience, we demonstrate the value of a complex systems approach using the TELLUS model. We test various combinations of system constraints, policies, and shock patterns, exploring the associated forms of resilience, and how this breaks down across systems and individuals. We find that although food systems and policies struggle to reduce the impact of repeated direct environmental shocks (i.e., robustness remains weak), well-timed policies that lower system constraints and promote early change to more sustainable practices can enhance shock recovery. Conversely, when faced with repeated general system shocks, we find system adaptation (increasing robustness), but note that this comes at production and livelihood costs. Finally, we highlight the value of policy commitment mechanisms, as we find the freedom to reverse ambitious policies jeopardises positive long-term food system futures, including resilience opportunities. Further we find the act of policy reversal seldom brings about the desired “return” to previous states (e.g., production levels), due to farms and farmland change being subject to other constraints (e.g., capital expenditure, soil degradation).

In sum, we show that good policy design must account for resilience, but to do so requires understanding how the interactions of individuals farmers change as a function of local projected shock patterns.

Summary

Food systems face numerous pressures over the next 30 years, including the challenge of feeding a growing population whilst large swathes of farming practices erode long-term production potential, harm the environment, and jeopardise farmer livelihoods. Compounding this situation, food production is at great risk from multiple forms of shock. Being at the nexus of ecology and climate (e.g., growing crops), as well as economies and markets (e.g., input and food prices, farm labour), food production is susceptible to shocks across multiple dimensions. In the past 5 years alone, we have seen multiple direct environmental shocks (e.g., extreme weather events including frosts, droughts, and waterlogging) and more general shocks that have affected food systems (e.g., global pandemics, war). Consequently, while policy-makers are faced with the non-trivial question of how to foster a change to greener, more inclusive farming that does not sacrifice production, without a comprehensive understanding of *resilience* within farming systems, any generated policies are doomed to fail in light of expected shock patterns around the globe. Food policy must at minimum avoid making food systems unintentionally more fragile (e.g., over-optimised supply-chains / markets), and at best should work with the food system to *enhance* resilience.

The challenge facing those concerned with resilience is two-fold: First, as a concept it is complex; covering the capacity of a system to not just withstand shocks (robustness) but also recover from them (recovery), and even re-organise in response to them (adaptation). Whilst conceptually linked, these different facets of resilience vary substantially across and within systems, each carrying different properties, advantages, and disadvantages and conditional degrees of interrelation. Second, resilience is both multi-scalar, and *emergent*. To capture it adequately, we must understand how it breaks down distributionally at the level of the individual, but then also how the collective behaviours of individuals produce the system-level response.

To appropriately capture the distributional and dynamic processes fundamental to food system resilience, we demonstrate the value of a complex systems approach. Within this approach we test various combinations of system constraints, policies, and shock patterns, exploring the associated forms of resilience, and how this breaks down across both system and individual outcomes. We find that although food systems and policies struggle to prevent repeated direct environmental shock impacts (i.e., robustness remains weak), policies that lower system constraints and promote early change to more sustainable practices (via temporal sequencing) can determine how effective recovery will be. Conversely, when faced with repeated general system shocks, we find system adaptation in the form of increasing robustness, but note that this comes at a cost of system-wide production and farmer livelihoods. Recovery instead remains limited without the assistance of well-designed policies. Finally, we highlight the value of policy commitment mechanisms, as the freedom to reverse ambitious policies jeopardises positive long-term food system futures, including resilience opportunities. Further we find the act of policy reversal seldom brings about the desired “return” to previous states (e.g., production levels), due to farms and farmland change being subject to other constraints (e.g., capital expenditure, soil degradation).

Taken together, we emphasise that good policy design not only requires in depth understanding of farmer characteristics (including the constraints they face), but also the form and nature of the projected shock patterns affecting that area, both locally and globally.

Food systems fragility

Food systems, as they depend on “climatic, biological, physical and chemical processes” (FAO 2022, p.3) are inherently vulnerable to shocks related to extreme weather events, natural disaster, pests, and diseases. Long term trends, such as climate change, water scarcity and pollution are also likely to negatively affect production over time. Geo-political events such as conflict, often co-occurring with some of the other shocks are also major drivers of shocks in both aquatic and land food production (Cottrell et al. 2019). More generally, shocks in other systems can also have serious implications for food production and processing – high energy prices for example affect energy intensive food system segments from the production and affordability of fertilizer, to heated green-house production, cool-chains, and food processing. Policy responses, whether to shocks or to other socio-economic drivers, can also generate shocks, either nationally (e.g., barriers to mobility during the pandemic) or across borders (e.g., export bans in producing countries at times of food inflation). While the analysis of whether specific types of shocks is not always conclusive (Zseleczky and Yosef, 2014), recent analysis of shocks by crop and country found that shocks have been increasing overtime. Growing automation and the role of social media in shaping attitudes to food (Hamilton et al. 2020) could also introduce new sources of shocks.

This diversity of shocks and of the system characteristics with which they interact, and the variety of responses including policy responses they generate, make it hard to generalize the impact pathways of shocks. Reference to the drivers of food security helps however map the entry points for those pathways and explore different examples – food security after all is the ultimate objective of food systems. Taking as a starting point Savary’s et al (2012) reinterpretation of the FAO’s household level food security framework, one can think of food security as depending from:

- Availability of food, which depends on primary production, food reserves and stockpiles and the stability of production
- Access to food by households, which depends on economic and physical access
- The ability of households to use food that is available and accessible, which depends on the food being safe, having nutritional content and from a host of socioeconomic factors.

The COVID pandemic experience saw relatively little impact on food availability per se (FAO 2021), but significant impacts of limited mobility and restricted trade, particularly on countries and regions severely dependent on food imports. Similarly, the impact of the war in Ukraine on food systems, at least in the first year of war, has been more in terms of decreasing physical access to food (through limitations to exports) than in terms of reducing availability itself. There is however an expectation that as land under cultivation decreases in Ukraine, and as the impact of high fertilizer prices globally reduces productivity going forward limits to the availability of food itself will also emerge (Vos et al., 2022).

A recent systematic review on household level food security and climate shocks identified lack of economic access as the most quoted source of impact, though the paper suggests that the literature might not be appropriately covering examples of large-scale reductions in production. Growing prices often compound income losses in reducing access to food. There is also evidence, however, of circumstances where climate shocks resulted in a significant decline in prices for specific goods, wiping out the income of specific groups of producers (evidence from Peru) thereby exacerbating their food insecurity (see also the price volatility in during the 1974 Bangladesh Famine; see e.g., Quddus & Becker, 2000).

The vulnerabilities in food systems exposed by the pandemic, the further strains added by the Ukraine war and the perception that food crisis are becoming more frequent are now attracting significant policy attention. While a number of policy measures, such as the designation of many food system workers as “key workers” exempt from lockdown requirements, have provided short term solutions to the challenges that the pandemic posed, there have also been calls for addressing food system resilience in more radical ways. Greater self-reliance and the reversing of environmental regulations to raise production are examples of the structural measures that some have advocated as part of the solutions.

Resilience in Complex Systems

Resilience can be defined as the ability of a system to absorb disturbance whilst retaining its basic function and structure. This can be further subdivided in to: (i) Engineering resilience (associated with the rate of recovery to an equilibrium state following a small perturbation); (ii) Ecological resilience (the magnitude of disturbance a system can absorb before shifting to an alternate regime – assuming multiple regimes exist); (iii) 'Socio-ecological resilience' (which extends (i) and (ii) to include the capacity of a system to adapt to prevailing conditions, for example through self-organization (Carpenter et al. 2001). High levels of resilience are deemed advantageous, but while broad definitions exist, measuring the resilience of large human-environmental systems is typically inexact, multi-featured, and in some cases largely subjective. Nonetheless, the consequences of lower resilience are clearly evident, out outlined in the previous section.

One of the potential systemic reasons for decreased resilience is the drive towards ever-increasing efficiency. This is seen in production in particular, and has led to many successes over recent decades (food security, improved human welfare). While efficiency is not in itself problematic from the perspective of resilience, a focus on narrow optimization, towards a limited set of system conditions (based on a small number of relatively simple quantifiable variables of short-term interest), may cause brittleness for the system as a whole. This happens when efficiency improvements are accompanied by highly optimized over-specialization, homogenisation, and the elimination of functional and capital-related redundancies. While under the expected 'average' conditions, efficiency may indeed be high, such systems may be considerably less capable of responding well to unexpected shocks (e.g., the economic, geopolitical, ecological, and social factors outlined in the previous section). Attempts to force complex systems in to optimal states can lead to ever-stronger, more forceful, and more expensive attempts at management, which ultimately exacerbate the more systemic problems. These problems stem from two central difficulties: (i) seemingly optimizable sub-domains cannot in any meaningful way be isolated from the dynamics of the wider system in which they are embedded (e.g., variations in social, economic, and biophysical conditions); (ii) even sub-domains are typically not 'simple' controllable and predictable entities, but are composed of interactive and adaptive individuals, and as such are potentially highly dynamic over longer timescales. A different mindset is to acknowledge change is inevitable and operating on multiple scales simultaneously. Responding to the relatively fast changes (e.g., weather, price fluctuations) comes naturally to decision-makers, but potentially more important for long-term resilience are the relatively slow changes (e.g., population growth, soil loss).

The concept of Adaptive Cycles is relevant here. This cycle (Holling & Gunderson, 2002) describes a notional progression of states: Opportunity -> rapid growth -> accumulation of capital and specialization of processes (loss of redundancy) -> loss of resilience -> crash -> release of capital -> re-organization -> opportunity…etc. In the lead-up to the crash, driven by specialization, systems may become locked-up in tried-and-tested processes, thus reducing innovation potential; costs of maintaining stability in this stage grow as a preoccupation with processes creates more 'command and control', potentially encouraged by poorly-designed subsidies that stifle innovation. Collapse of the structure of the system is then seen as an inevitable part of a natural cycle if conditions of increased specialisation, reduced redundancy (and others) are met. In principle, greater resilience and increased capacity to adapt to future changes can be promoted through: (i) increased diversity and redundancy at all scales (a source of future options and a system's capacity to adapt to new conditions); (ii) promotion of variability (to promote adaptative capacity, maintaining the ability to respond to both short term shocks and longer term trends); (iii) balancing modularity and connectivity (compartmentalizing enough of the system elements to prevent domino effects, while allowing sufficient connections for efficiency); (iii) not forgetting slowly-changing factors which set the context for rapid responses (e.g. valued ecosystem services); (iv) identification of potentially beneficial and harmful feedback cycles (e.g. the spread of improved farming practices, the loss of biodiversity); (v) promoting trust, functioning social networks, and effective leadership (including at institutional levels) promoting adaptation of social norms, rather than an anchoring activities in the past (Diamond, 2005); (vi) promotion of innovation and learning, to avoid locking-in fixed behaviours (e.g. through misplaced subsidies). Skilful decision-makers can avoid the crash stage described above and 'jump' the system to a different stage (for example, by intentionally creating small scale disturbances during the 'loss-of-resilience' stage, which releases capital and restarts the opportunity/innovation phase). Highly-optimised supply chains, dependence on a relatively small number of large suppliers (e.g., fertilizer), narrow ranges of farming practices (including seed/fertiliser types, mechanisation trends), large buying power focused in a relatively narrow range of actors, run the risks of narrow optimisation as outlined above. The variability in local food production systems, combined with global scale shocks such as Covid and the Russia-Ukraine conflict, provide rich examples of perturbations.

Given the complexity of food production systems, their multi-scale nature, and the heterogeneity both between and within geographical regions and different economic sectors, human expertise alone is insufficient for decision-making. Reductionist approaches, where system behaviour (and response to policy) is parameterised in simplified models, entail considerable risks of producing simplified representations of the system response. It is to empirically-informed numerical models that we must look in order to include the 'messiness' and complication of real-world systems. Agent-based models (ABMs) provide much of the flexibility required, as they can be specified to arbitrary levels of granularity and can incorporate multiple agent types, behaviours, and their interactions. ABMs in such contexts are typically explicitly spatial and naturally have the potential to produce emergent/self-organized structure and behaviours, mirroring real-world systems. Assuming top-down control results in the desired system0level outcomes, without including bottom-up responses, entails significant risks of unintended consequences. In the model presented here (TELLUS), top-down controls (policies) can be imposed and the majority of the system response is emergent, including the spatial distribution of activities, structure of social networks, nature and strength of feedbacks. Both time series data and summary statistics on agents and system-wide phenomena can be collected from the model. As such, quantitative metrics such as the sensitivity to shocks and associated recovery rates can be calculated.

The TELLUS Model

The TELLUS model is an agent-based simulation concentrating on the behaviour of interacting populations of individual farming agents (Pilditch et al., *under review*), with particular regard to fostering regenerative farming shifts. Farmer agents attend to their surrounding context, including the ecology of their fields (soil quality), the (imperfect) information available to them (e.g., first-hand observations, agricultural extension agents, peer networks), and their local understanding of the market (e.g., suppliers, buyers, and cooperatives). The decisions they make seek to fulfil their individual goals, given the constraints placed upon them by their conditions. Previous work has shown the how these constraints limit the capacity of farmers to change and adapt to new policies and conditions (*Ibid.*). Diversity amongst individual farmers (geographical, socio-economic, psychological, and experiential dimensions) and in the way they connect with the system (through social, cultural, and economic conditions) affects not only the distribution of outcomes among these populations (e.g., growing inequality in production, livelihoods, and environmental gains), but also impacts the rate of emergent change across the system. The feedbacks within the system (e.g., the actions of farming peers reinforcing the tendency to engage in those actions in future), combined with the heterogeneity represented within the system, allowed previous work to demonstrate temporal sensitivities and tipping points that should be considered in policy design when aiming to promote system change.

Farmer agents make a range of decisions based on objective (economic) and subjective (psychological) factors. These decisions include (but are not limited to) farming practice choices, knowledge acquisition, input purchases and product sales, farm system exit (and entry), farm upsizing/downsizing, and contracting (see Pilditch et al., *under review* for details). They are informed by the farmers experienced context, which is the product of their own and others behaviour (see Fig. 1 for an overview of the farmer decision context). Each farmers experiences are different, evolving endogenously within the model as a function of each farmers interactions with their local environment (e.g., their successes and failures, the actions of their peers, their exposure to local markets and advisory services, policies and shocks), and the psychological lens through which they interpret the outcomes of those interactions (e.g., their income, cultural, and reputational preferences, levels of risk-aversion, time-horizons for forecasts/projections, perceptions of credibility for communicated information).

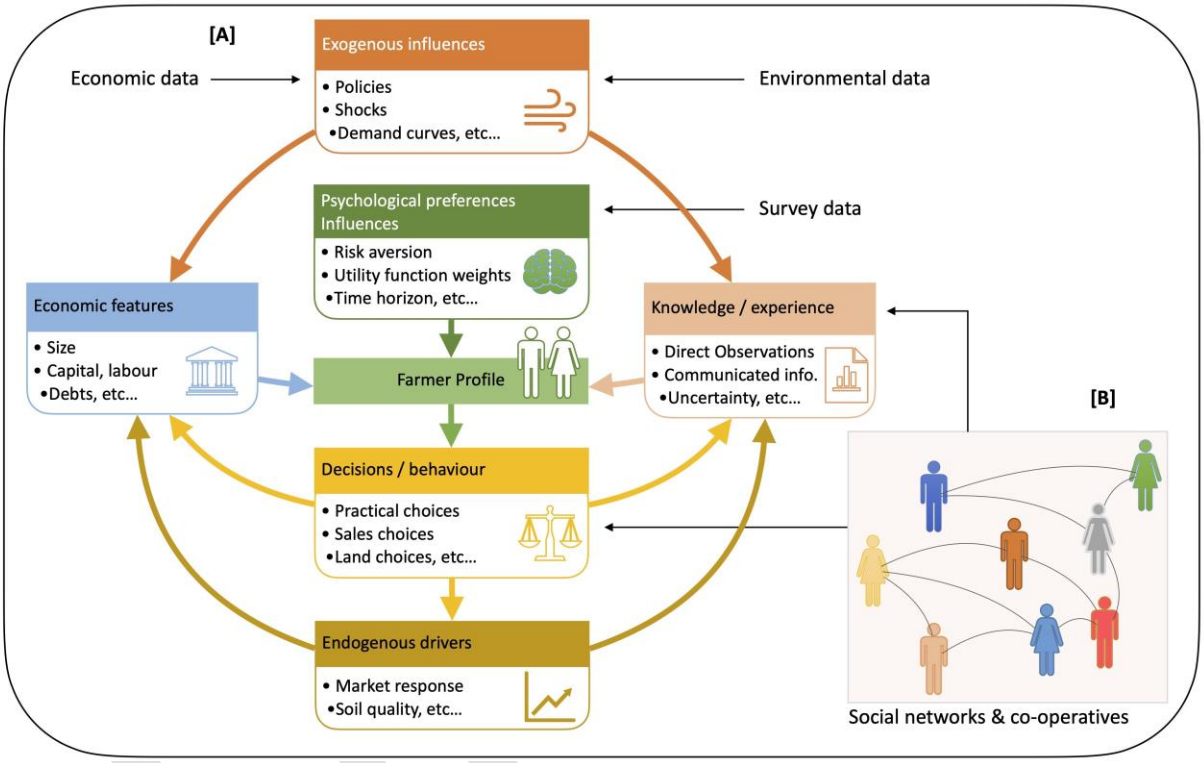

Figure 1. Farmer decision context within the TELLUS model [A]. Each farmer bases their decisions on their current knowledge-state (e.g., experiences, perceptions of peers [B] and markets, uncertainties), preferences, and economic status. The outcomes of these decisions affect the decision context at subsequent time-steps, for both themselves and their peers (e.g., via communication and market impacts). This allows TELLUS to capture complex features of the farming system, such as the interdependence between the actions of farmers. [Taken from Pilditch et al., under review].

Simulated farming system outcomes, including the potential impact of both shocks and policies, ultimately rests on the awareness, capacity, and willingness of farmers to change their behaviours given their experience, preferences, and expectations. In capturing the complexity of the farming system (i.e., the heterogeneity among actors, their connectedness, interdependence, and capacity to adapt to conditions) at the granular level of individual farmers, we can capture the wide varieties of emergent responses. Furthermore, this approach allows us to attain a deeper evaluation of constraining influences, decision drivers, and, ultimately, policy efficacy than with coarser models (see Pilditch et al., *under review*).

Extending the work of Pilditch et al (*under review*), here we focus on the interaction of different shock patterns with various policy bundles within the complex, dynamic, multi-variate food supply side system. In so doing, we are able to provide novel insights regarding the robustness to shocks, recovery from shocks, and adaptations to future shocks across multiple food system outcomes of interest (food production, farmer livelihoods, and environmental outcomes) at both the system level, but also distributionally across farming populations. Furthermore, this "scenario testing" approach allows us to identify characteristics of food systems that may exacerbate or ameliorate these different forms of resilience (e.g., reducing robustness to shocks, but enhancing recovery), and further how these effects are moderated by different policy bundles (e.g., a policy that increases vulnerability to a particular shock among a particular portion of the farming population). Finally, to complete shocks, policies, and resilience (response) feature set, the model incorporates a policy-maker-reaction component, wherein backtracking / reversals that tempt policy-makers are included as potential dynamic responses to changing conditions (e.g., reversing a policy given recent production losses). Taken together, the TELLUS model enables us to explore critical questions regarding the interplay of food system characteristics, policy bundles and shocks on the inherently dynamic, adaptive, and emergent effects that are resilience types. Furthermore, it can make these projections in a quantified manner, enabling future testing of sensitivities.

Shocks, resilience, and policy reversals

To better understand food system resilience, we assess a range of relevant scenario characteristics in combination with various policies and shock patterns. This scenario testing is designed to provide a broad diagnosis of sufficient granularity to inform judgements of expected forms of resilience across food system outcomes to different types of expected shock patterns, and how effective policies may be regarding their intended effects, as well as their unintended consequences (e.g., reductions in resilience).

Barriers to Innovation Archetypes. Following barriers to innovation archetypes laid out in Pilditch et al. (*under review*), and grounded in economic literature (Mwangi & Kariuki, 2015), we use two idealised archetypes; economically constrained, versus economically unconstrained systems. Specifically, we assess the impact of the following constraints on farmers; (low) capital, (high) debt, (high) borrowing rates, (poor) access to finance, (small) farm sizes, (low) levels of farm ownership, (low) labour availability, and (low) off-farm income opportunities. Further details of this decomposition may be found in [the Supplementary Materials Doc: Scenario Settings, along with further archetype breakdowns].

Shock Patterns. Within the TELLUS model, shock patterns are fed in as time-series data. Shocks can be characterised across 4 types of impact; direct loss of yield (i.e., crop failure), labour shortages, loss of demand, and input cost increases. In this way, real world shocks can be characterised across by their pattern of impacts, based on historical cases. Impacts are defined in percentage impacts (e.g., 50% loss of yields) and when active are applied across the entire simulation (i.e., we assume no a priori differential impact within the system; any distributional differences in knock-on impacts are thus the result of endogenous system responses). This quantified approach, when coupled with the time series nature of shock pattern inputs, allows us to describe the severity, duration, and frequency of shocks. Although this flexibility affords myriad possibilities for testing, for our current illustrative purposes, we demonstrate the following shock patterns for comparison [complete details for all shock patterns are found in the Supplementary Materials Doc: Scenario Settings]:

Baseline. For comparison purposes, we have a condition in which no shocks occur.

Direct Environmental Shocks. Although such a term is broad, here we consider this type of shock as one that directly impacts harvest size (yields)[1], such as droughts or extreme weather events.

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[1] Direct environmental shocks affecting yields are not assumed to affect the underlying soil quality in the current version of TELLUS, though subsequent model versions could build this in.

Additionally, we assume this type of shock to impact supply input costs (e.g., representing lost assets and infrastructure impacts of extreme weather damage). In the current scenario testing, we assume these shocks to occur at increasing frequency (years 6, 13, 19, and 23), but of equal proportionate severity (~90%; i.e., yields reduced by 90%, supply costs increased by 90%) over a duration of two years per shock. Although expected direct environmental shock patterns vary (e.g., regional extreme weather patterns, regional pest threats), here we select a pattern of increasing frequency as broadly representative of current expectations.

General Food System Shocks. Given recent history, there has been a sharp rise in awareness of the impact of war (e.g., crisis in Ukraine, see Vos et al., 2022) and pandemics on the global economy (FAO 2021), with trends in deforestation (and subsequent rises in disease vectors due to decreases in natural predators) argued to contribute to an increasing prevalence in future (Tollefson, 2020). Consequently, we model a general food system shock as reducing product demand (whether via interrupted supply chains, or sudden shifts in required products), shortages in available labour (e.g., directly via disease impact, or government measure), and supply input costs (e.g., via similar supply chain disruption). For ease of comparison, we assume these shocks to also occur at increasing frequency (years 6, 13, 19, and 23), but of equal proportionate severity (~90%; i.e., demand reduced by 90%, available labour reduced by 50%, supply costs increased by 90%).

Although, as noted throughout, many possible shock patterns are possible to test with the TELLUS model, for now we demonstrate the above as broadly illustrative of potential impacts on the global farming system over the next 30 years.

Policy Packages. We compare a baseline scenario (a farming-practice-agnostic production subsidy, that is removed at year 6) to two regeneratively focussed policy bundles: a regenerative land-based subsidy, and a "priming" policy bundle. Introductory details are provided in Table 1 below, with more complete descriptions found in the method section below. These policies were selected for comparison based on their purpose and ambition in changing the farming system, such that the impact of constraints is more clearly highlighted (see Pilditch et al., *under review*), but also the impact of shocks and policy reversals may be made clear.

Table 1. List of selected policies implemented in TELLUS simulations.

Policy	Description	Detail
Baseline	General Production to Nothing	$0.02 (per kg/practice; lasts for first 6 years of simulation only). This is agnostic of implemented practices.
Regenerative subsidy	A fixed, land-based subsidy based on amount of land regeneratively farmed.	Baseline, then: $100 per hectare per regenerative practice. From year 6 onward.
Priming policy bundle	A “front-loaded” regeneratively focussed land subsidy that tapers over time, plus market, input, retirement, and information dissemination policies.	Baseline, then: A Priming subsidy starts at $500 per hectare per regenerative practice (beginning in year 6), tapering down to $100 per practice over the next 12 years, then becoming a carbon tax on non-regenerative practices beginning at -$10 per hectare per practice, rising to -$200 per hectare per practice over the span of 10 years. Plus: • an increasing percentage tax on buyers trading in non-regenerative goods (10%, increasing a further 10% every 3 years, rising to 80%), • incentivisation for co-ops to facilitate regenerative production among members, • a ban on artificial pesticides, • an early retirement policy (50yrs+), rising by 5 years every 6 years, • enforcing GEA and agronomist practice advice to focus on regenerative practices, • and encouraging the use of the internet among all farmer archetypes to share new practices.

Debt Forgiveness. Farmer debt has been identified as a key economic constraint (see e.g., Mwangi & Kariuki, 2015, but also Pilditch et al., *under review*). Given the potential interaction between constrained farmer choices, policy take-up, and resilience, we orthogonally test a separate, debt forgiveness policy across farming populations. When this policy is active within a simulation, all debt owned by farms in year 1 is forgiven, but at no further times during the simulation. It should be noted that this policy should only impact economically constrained systems, as farmers in unconstrained systems start with negligible levels of debt. Consequently, we consider this debt forgiveness policy as an illustrative example of a potential resilience-focussed policy lever (see e.g., incorporation of farmer debt forgiveness into US Government Inflation Act, 2022).

Policy Reversals. Finally, given the increased relevance knee-jerk policy-maker reactions to recent food system shocks (see e.g., nationalised/self-sufficiency reaction to crisis in Ukraine; Strange et al., 2022), and the likelihood of further shocks within the next 30 years, it is important to better understand the potential impacts these reversals may have on food system outcomes. To test this, we test a policy-reverser enabled condition against a baseline in which no reversals can occur. The reversal consists of a simple policy reversal *back to an agnostic production subsidy (i.e., the Baseline policy settings)*. It is triggered by a recognised loss in production of >= 10% across two consecutive years. This reversal capacity is dynamic, in that the reversal is an endogenous response to conditions within the system. The capacity is set to enabled/on or disabled/off.

Results

We focus on three SDG-relevant food system outcomes of interest: levels of food production (i.e., annual yields), farmer livelihoods (here considered as farmer *survival* within the system), and environmental change (here a representative “soil quality” amalgam measure). Each of these outcomes is considered contemporaneously, and is assessed for the three identified forms of resilience: robustness (initial “depth” or impact of a shock), recovery (the speed of return to pre-shock levels), and adaptation (here we consider this in terms of *improvements* in robustness/recovery over time).

Our findings reveal that different shock patterns lead to different resilience profiles not only distributionally across farmer populations, but also across outcomes of interest. Furthermore, whilst shocks are shown to be capable of undermining policy goals (e.g., slowing/interrupting attempted regenerative change) – where this is not already compromised by existing constraints – we find these long-term harms to be *compounded* rather than *ameliorated* by policy reversals. These findings emphasise the importance to policy design of not only acquiring sufficient information about farmers and their constraints, but also understanding and anticipating potential shock patterns. Coherent, comprehensive design can not only target key difference-makers within a system (e.g., debt forgiveness enabling change, and in turn enhancing recovery capacity), but can also assist policy-makers in resisting policy reversals that in fact bring about worse outcomes than those they are intending to avoid.

Shocks and Resilience

The findings described here first cover the impact of shocks on our three main variables of interest (production, environment, livelihoods), with reversals and debt forgiveness set to one side. We then explore the role and impact of policy reversals in the section that follows, before covering the influence of debt forgiveness.

Direct Environmental Shocks:

Constraints and Shocks. We find that direct environmental shocks appear to have a larger impact on production in unconstrained systems – at the point of the shock (Fig. 2). However, this does not mean an unconstrained system is more fragile, but rather a constrained system is already approaching a floor in the amount of production. Conversely, an unconstrained system has higher average yields, which gives the impression of **deeper shocks in absolute terms** (i.e., the system appears less *robust*), but this is only part of the picture. When one considers the **recovery** dimension of resilience, we can see that in unconstrained systems recovery of production compensates for the increased shock depth. More critically still, as the unconstrained system enables uptake of the priming policy bundle, we find this policy **improves recovery** with subsequent shocks (despite appearing inferior after the initial shock, due to yields taking time to improve under regen practices).

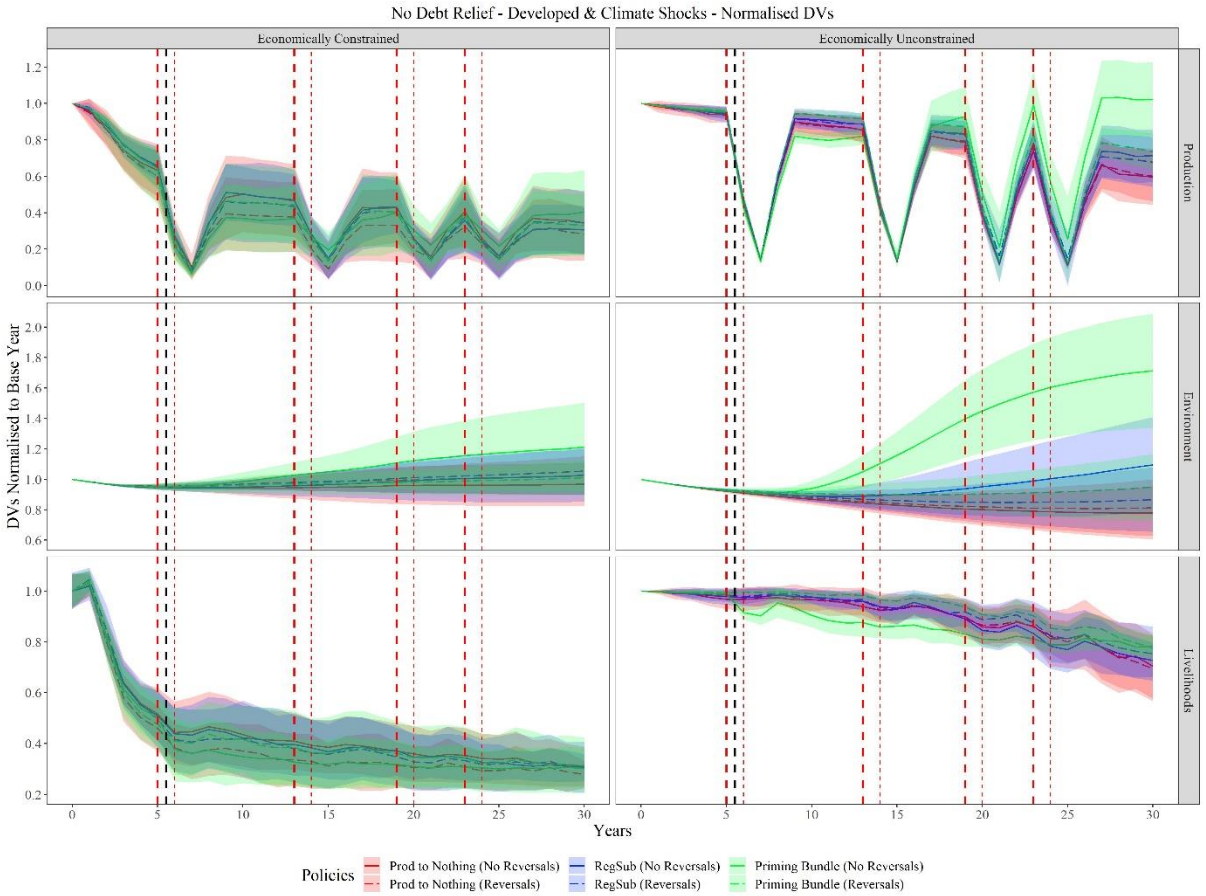

Figure 2. Policy and policy reversal impacts under direct environmental shocks condition (at red dashed vertical lines) on total food production (top row), average farmland soil quality (environment; middle row), and number of farmers (livelihoods; bottom row), using mean values across a 30-year period, normalised to baseline values. Economically constrained (left-hand column) and unconstrained (right-hand column) farmer scenarios are tested, and majority large-holder system is illustrated. Policy scenarios shown are: no subsidy (red), a fixed subsidy for regeneratively farmed land (blue), a "priming" regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information campaign (green). Solid line-types = no reversals; dashed line-types = reversals. Ribbons reflect +/-1 S.D.

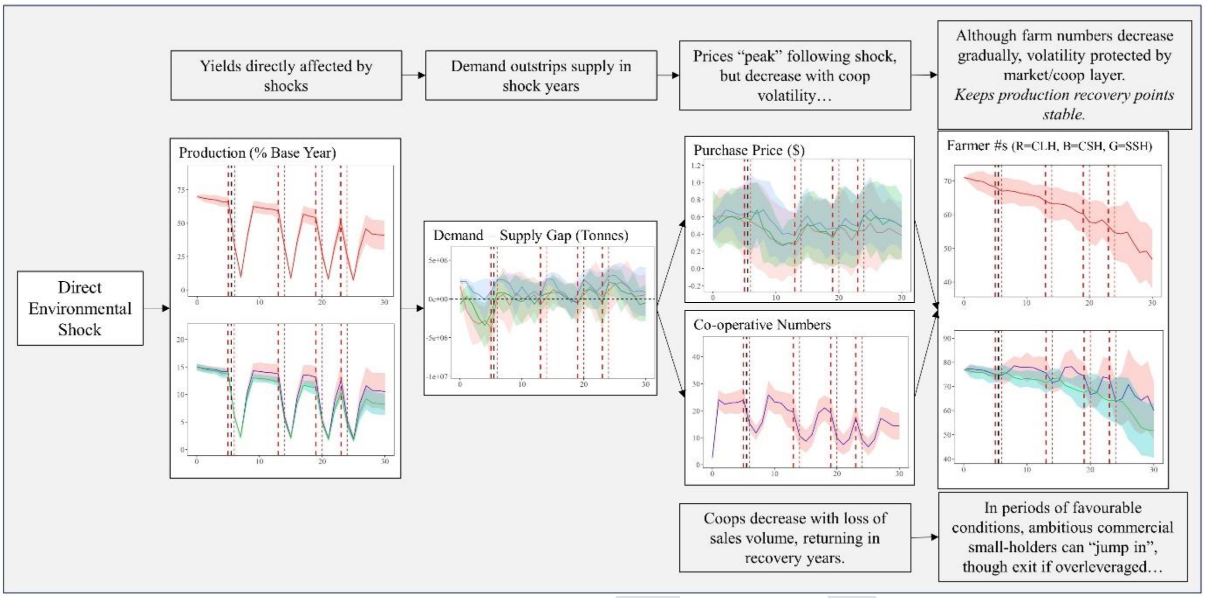

Figure 3. Illustrative causal diagram for direct environmental shock impact. Facets from left to right: Production (% base year), split by Commercial large-holders (top) and commercial and subsistence small holders (blue and green; bottom); total product demand – supply (tonnes), split by product types; Purchase prices (buyers offering to farmers; $/kg), split by product types; Co-operative numbers; Farmer livelihoods (number of farms), split by Commercial large-holders (top) and commercial and subsistence small holders (blue and green; bottom). Ribbons reflect +/-1 S.D.

Direct environmental shocks distributional outcomes. Although direct environmental shocks affect total production, we find there is minimal impact on livelihoods and environment outcomes – constraints and policies have more impact on these variables. This is in part attributable to the direct yield-impact nature of direct environmental shocks, but also to the market offering higher prices for the scarce product in shock years, which reduces the risk to commercial livelihoods (illustrated in Fig. 3).

When we dive deeper into different farmer archetypes, we can see that although commercial large-holders are more generally robust to direct environmental shocks (right-hand facet of Fig. 3), commercial small-holders are more readily able to enter the system post-shocks to take advantage of any newly available land and demand-supply gaps. It should be noted that this does produce some turnover in commercial small-holders, as the next shock can force the most vulnerable/overleveraged out. However, one related explanation for this distributional difference is that cooperatives can often "take the hits" of direct environmental shocks, with many going out of business following each one, before new small cooperatives are then created post-shock (see Fig. 3; Cooperative numbers). This has implications for considerations of **resilience at different scales**, given this turnover seems to provide some protection to farmer livelihoods in the direct environmental shock condition (see Fig. 2).

In relation to the market impact of the direct environmental shock, we also find that there are higher numbers of production contracts undertaken (see Fig. A1), suggesting responsiveness from both producers and buyers to seek security in light of perceived volatility. This may be driven by buyers offering more lucrative terms in the direct environmental shock condition, and producers being more willing to accept poorer terms in general system shock condition.

Lastly, there are minimal signs of system **adaptation** to shocks at the farmer level, as the depth and speed of recovery remains constant throughout. This is as expected given that direct environmental shocks are a direct impact on yields, which cannot be expected to show signs of adaptation without specific inclusion of mechanisms representing potential technological innovations (e.g., further engineering of extreme weather-resistant crops).

General System Shocks:

Different shocks, different mechanisms. We find that unlike direct environmental shocks, general system shocks (which affect labour, product demand, and input costs) impact production in more long-lasting ways (Fig. 4) – given an unconstrained system that is not already approaching a floor. Although shock **depth** appears to be lower for production than in direct environmental shocks – and depth decreases with each shock, **recovery** is substantially hindered as the system begins to shift as follows:

Each general system shock forces a “step-down” effect in production, that coincides with a simultaneous step-down effect in livelihoods. This is attributable to farmers adapting to labour market constriction through down-sizing operations, from which it is then harder to recover. In fact, *this appears to affect commercial large-holders* – whom require the most substantial amounts of labour **-** *the most* (Fig. 5).

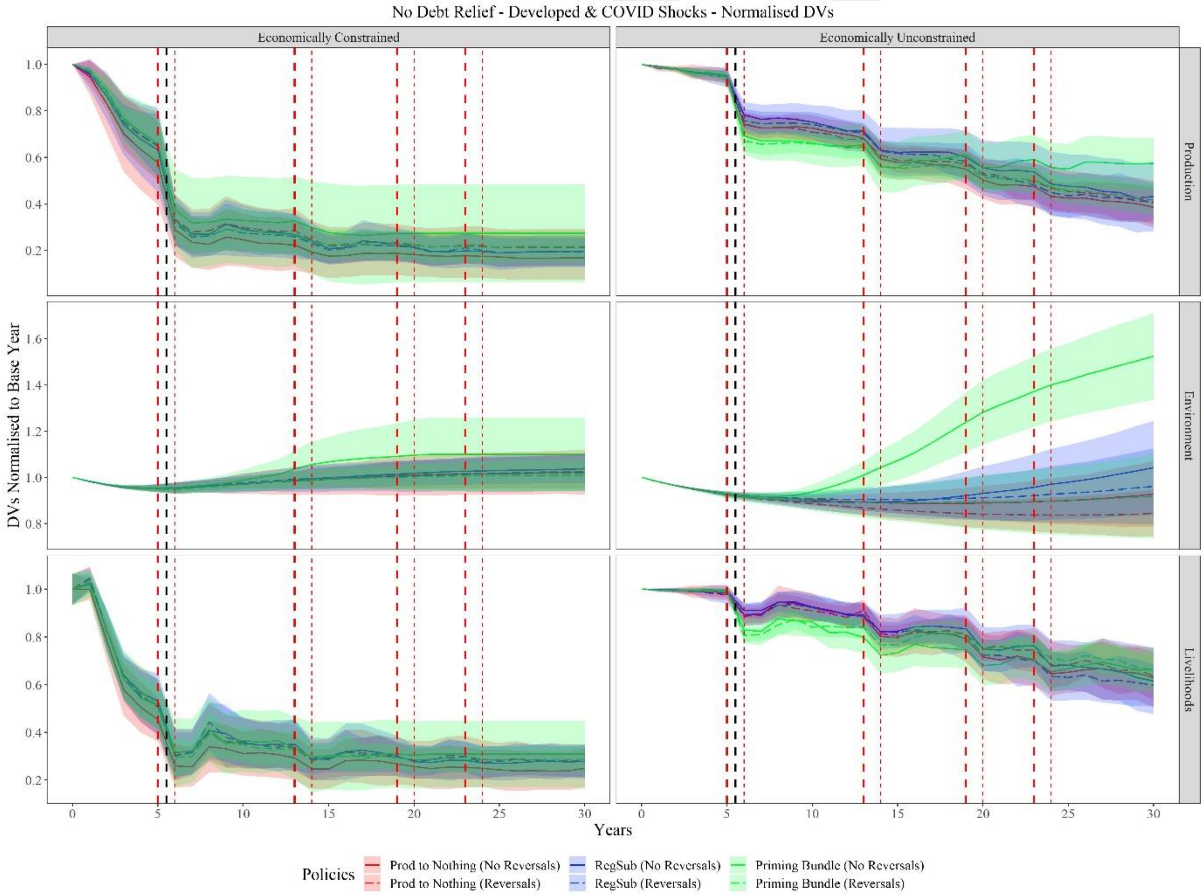

Figure 4. Policy and policy reversal impacts under general system shocks condition (at red dashed vertical lines) on total food production (top row), average farmland soil quality (environment; middle row), and number of farmers (livelihoods; bottom row), using mean values across a 30-year period, normalised to baseline values. Economically constrained (left-hand column) and unconstrained (right-hand column) farmer scenarios are tested, and majority large-holder system is illustrated. Policy scenarios shown are: no subsidy (red), a fixed subsidy for regeneratively farmed land (blue), a “priming” regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information

campaign (green). Solid line-types = no reversals; dashed line-types = reversals. Ribbons reflect +/-1 S.D.

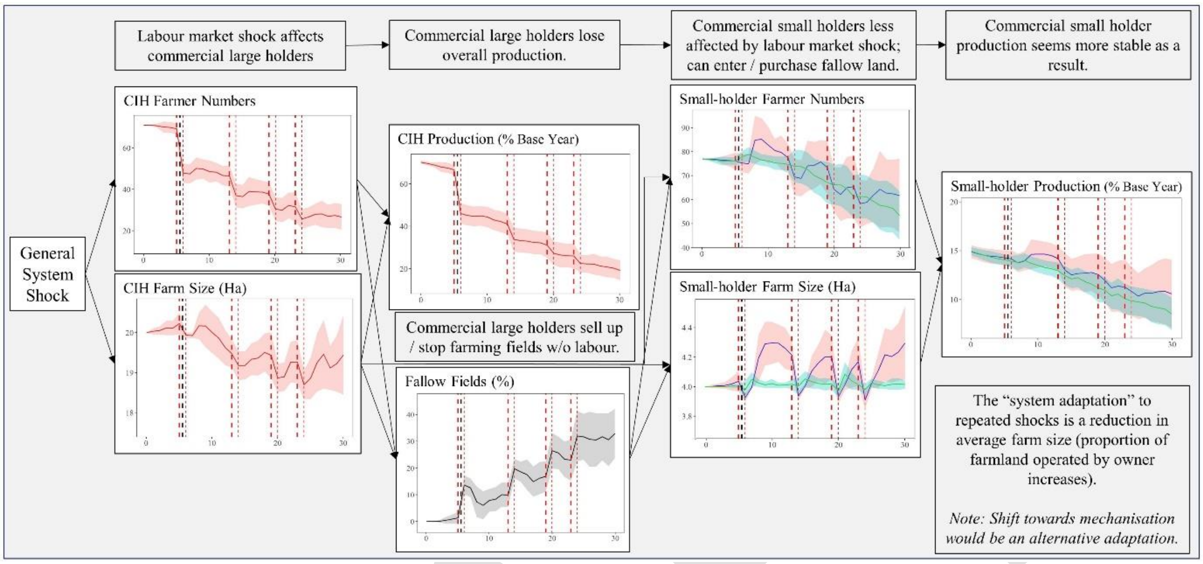

Figure 5. Illustrative causal diagram for general system shock impact. Facets from left to right: Commercial large-holder numbers (top) and mean farm-size (hectares, bottom); Commercial large-holder production (% base year; top), and Percentage of farmland fallow (bottom); Commercial and subsistence small-holder numbers (blue and green; top) and mean farm-size (hectares, bottom); Commercial and subsistence small-holder production (% base year; blue and green). Ribbons reflect +/-1 S.D.

As larger holders are more dependent on a healthy labour market, and in addition have the largest amounts of land to turn fallow if unused, they can struggle the most to bounce-back. This is not because of their finances, but rather the way larger-holders, *if a general system shock forces them to sell land*, can struggle to re-acquire all their previous land as it may be acquired by new and recovering local commercial small-holders (see Fig. 5 for illustration of this causal chain). More precisely, post shock, a large holder begins to gradually reacquire some of the land they had given up (if it is not already sold to another owner), but as new and existing commercial farmers on the periphery of the large-holder's old farmland boundary recover, they can each individually purchase some of the land closest to them.[2] With each shock, this "eating away" can gradually erode large-holders capacity to produce. This highlights the importance of representing and understanding geospatial dispersal of farmers to capture key emergent phenomena stemming from behaviours that interdepend. Although this has implications for potentially reducing inequality, it comes at the cost of an overall less productive system. This is particularly true if land is acquired by a (*ceteris paribus*) more practice constrained farmer (i.e., a small-holder with less capacity/incentive for regenerative practices).

Breaking this down by resilience categories, we see commercial large-holders are worse affected by general system shocks both in terms of depth (robustness) and recovery, commercial small-holders are affected in terms of depth (robustness), but not to the same degree (the exchange effect described above affects them less), whilst they recover more readily as a population. Meanwhile

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[2] This is moderated by policies. The priming policy means more small-holders have acquired funds to spend on land purchases, but additionally at least means the newly acquired land is likely to be farmed regeneratively – hence environmental outcomes actually improve.

subsistence small-holders are more robust to the shock (as they do not depend so heavily on markets and labour), but experience gradual decline regardless (e.g., via increasing input costs).

Unlike the resilience response to direct environmental shocks, which remains constant throughout, there appears to be evidence of system adaptation to general system shocks. More precisely, the effect of general system shocks (e.g., the depth of the "hit" to production) decreases over time, as a result of the average farm-size reducing. In essence, the repeated shocks to the labour market most greatly affects farms that are the most overleveraged / dependent on that labour market (see Fig. 5). The larger a farm, the more labour is required to run it, ceteris paribus. Consequently, as the largest farms are reduced in size (via the process outlined above), farmland becomes less concentrated, with a higher proportion of farmland operated by the owner of that farm. This trend may decrease production efficiency in a system without shocks, but in a system affected by repeated shocks, this emergent adaptation – by reducing the impact of general system shocks – preserves production and livelihoods (and under the correct policy conditions, continues to enable environmental gains).

Finally, we again see that environmental outcomes, unlike production and livelihoods, are not so directly affected by shocks (though note that our environmental outcome is an *average* soil quality), but are more affected by constraint and policy conditions (see Policy Reversals below).

Policy Reversals

Reversals from misunderstood constraints. Before addressing the role of policy reversals in response to exogenous shocks, it is first worth addressing the likelihood and impact of reversals *in general*. As outlined in Figures 6 and 7 below, reversals intending to boost production are likely when production is curtailed by other factors. More precisely, as constraints impact production (notably via farmer exits), there is a high likelihood of policy reversal in an attempt to boost immediate production (Fig. 7). **The desired gain in production does not materialise** (nor does so across any shock condition). The forgone "loss" incurred by a reversal in these instances is minimal given the prohibiting influence of constraints, but this is indicative of a **wasted opportunity**, as additional intervention (e.g., debt relief, see below) could better preserve livelihoods, retaining production, and enabling further policies for long-term, regenerative production.

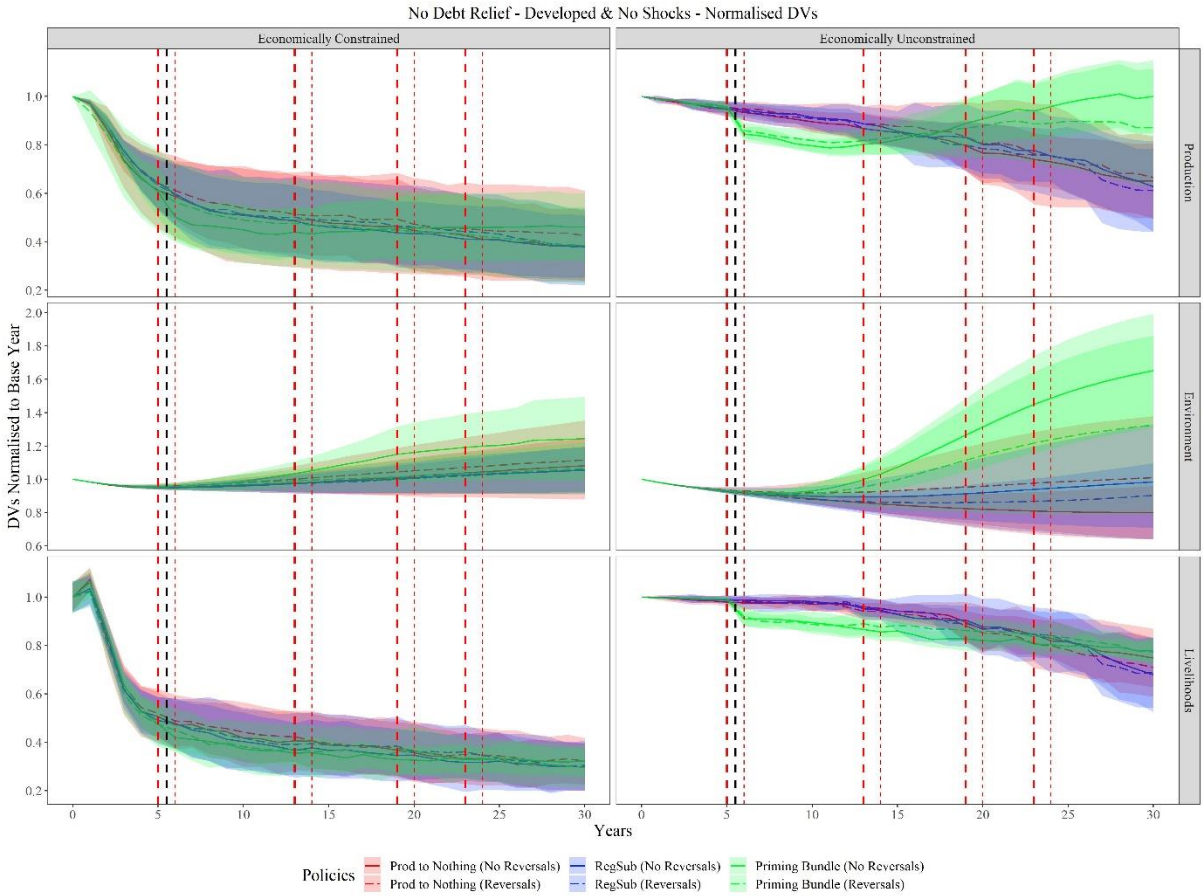

Figure 6. Policy and policy reversal impacts under no shocks condition (at red dashed vertical lines) on total food production (top row), average farmland soil quality (environment; middle row), and number of farmers (livelihoods; bottom row), using mean values across a 30-year period, normalised to baseline values. Economically constrained (left-hand column) and unconstrained (right-hand column) farmer scenarios are tested, and majority large-holder system is illustrated. Policy scenarios shown are: no subsidy (red), a fixed subsidy for regeneratively farmed land (blue), a "priming" regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information campaign (green). Solid line-types = no reversals; dashed line-types = reversals. Ribbons reflect +/-1 S.D.

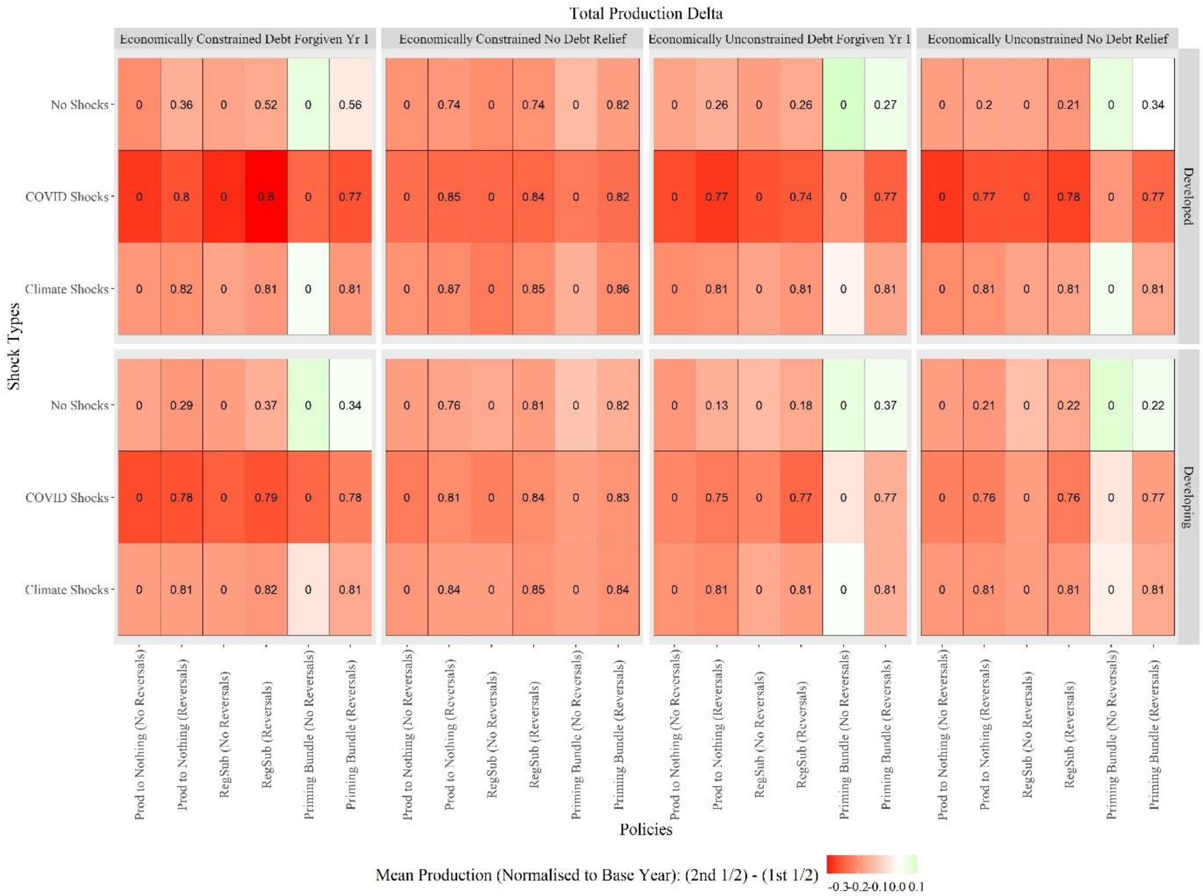

Figure 7. Policy and policy reversal impacts on total food production, using mean values across a 30-year period, normalised to baseline values, with second 15 years – first 15 years. Negative (red) values indicate decreased production over time, whilst positive (green) values indicate production has increased. Economically constrained with year 1 debt forgiveness (left facet column), economically constrained with no debt forgiveness (centre-left facet column), economically unconstrained with year 1 debt forgiveness (centre-right facet column), and economically unconstrained with no debt forgiveness (right facet column). Majority large-holder vs majority small-holder systems (top vs bottom facet-rows, respectively). Policy scenarios shown (across X axis) are no subsidy, a fixed subsidy for regeneratively farmed land, a "priming" regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information campaign. Shock patterns (none, general system, and direct environmental) are shown on the Y axis, and proportion of time under policy reversal is shown within grid-cells.

Reversals compound shocks. Irrespective of shock type, a short-term impact on production means reversals are highly likely to occur, regardless of economic constraints or active policies (Fig. 7). Importantly, reversals intended to improve production ***never do so***, and through undermining environmental gains possible through e.g., the priming policy bundle, not only **compromise long-term environmental goals**, but worsen **both long-term production and the *capacity to recover from future shocks***. This effect is particularly notable in recovery post direct environmental shocks (Fig. 2), whilst general system shocks (Fig. 4) long-term production decreases via livelihood dynamics, more so than failed policy efficacy (though the priming policy – if not reversed – does see environmental outcome improvements among surviving farmers).

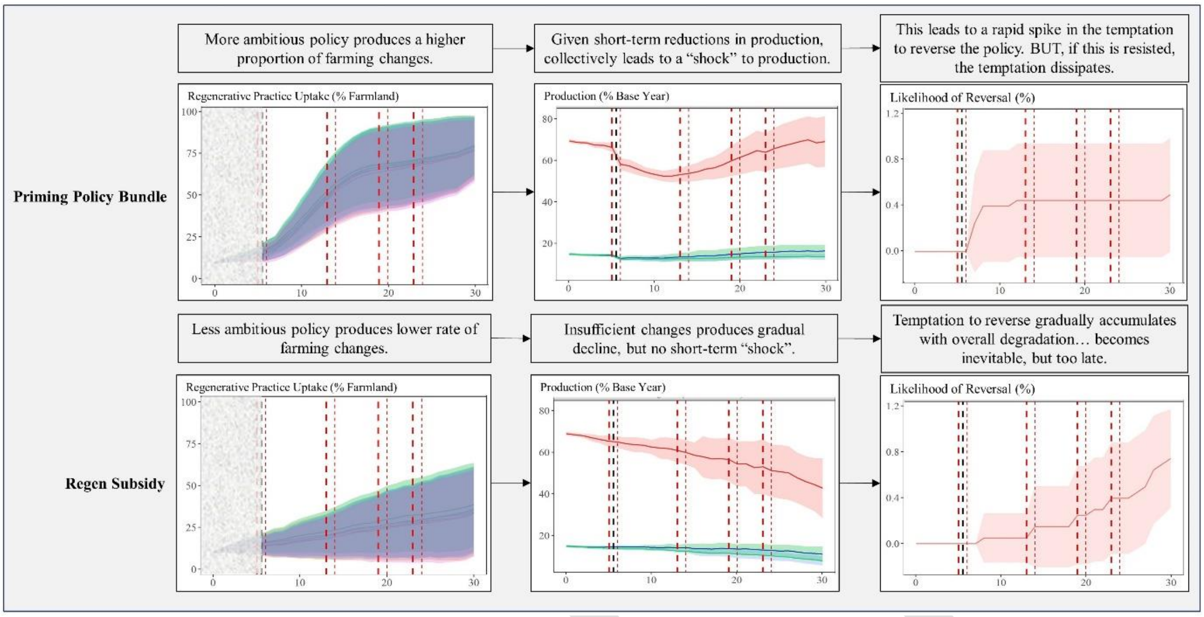

Figure 8. Illustrative causal diagram for policy impact on reversal likelihood. Top row illustrates a more ambitious policy bundle (priming policy bundle), and bottom row illustrates a fixed regenerative subsidy. From left to right: The effect of policies on the percentage of farmland regeneratively farmed (i.e., regenerative practice uptake); Production (% base year), split by Commercial large-holders (red), Commercial small-holders (blue), and subsistence small-holder (green); and the cumulative likelihood of policy reversal, based on production losses year-to-year. Ribbons reflect +/-1 S.D.

Policy Ambition Impacts Reversal Temptation. Although the absence of constraints lowers the likelihood of reversals, it should be noted that policies can themselves produce different patterns of reversal likelihood (Fig. 8). More precisely, whilst a fixed regenerative subsidy is gradually more likely to produce a reversal as it fails to incentivise sufficient change in the long-term, the priming policy is most likely to cause a reversal within the first 5 years of implementation, **but is then no longer likely to tempt a reversal**. Put another way, *if there are sufficient commitment mechanisms to last this 5-year period, then the concerning production loss reasons for being tempted to reverse dissipate*, and both the production and environmental gains result.

Debt forgiveness

In general, year 1 debt forgiveness brings a constrained system close to alignment with unconstrained systems (see e.g., left-hand pair of columns, Fig. 7, but also see Fig. B1 for example time series impact across main outcome variables). More precisely, it prevents constraint-based farmer exits from the system (and the losses in production that result), lowers the related risk of policy reversals, and enables responsiveness to more effective regeneratively-focussed policy bundles (i.e., the priming policy bundle). It should be noted that the impact of introducing the priming policy bundle on the temptation for policy-makers to reverse the policy early on remains the same (Fig. B2), as the production "shock" is a consequence of farmer choices, not exits.

In the context of direct environmental shocks, debt forgiveness does not produce any additional benefits in terms of resilience, beyond those demonstrated by unconstrained systems (relative to constrained systems). As a result, policy reversals also remain just as likely (and potentially damaging/undermining). However, debt forgiveness does appear to affect general system shock impacts differently. As the nature of a general system shock affects labour markets, fully unconstrained systems have more flexibility/surplus in the labour markets to help mitigate some of the shock **depth** (e.g., Fig. 4). Conversely, a constrained system with debt forgiveness has no such labour "buffer", and consequently sees a deeper impact of the initial general system shock on production (see Fig. B3). Fortunately, the lack of substantive debt does mean there are less farmers needing to sell-off farm-land assets the moment it is not producing, preventing some of the deleterious mechanics described above. Taken together, this latter point illustrates the importance of identifying active constraints not only in a system in a "stable" state, but also within the context of likely shock patterns. Policies not taking this nuance into account run a risk of inefficacy.

Conclusions

Across our shock, policy, and archetype manipulations, we find a number of important nuances and interactions when we consider the issue of resilience (and responses to shocks in general):

Different shocks affect food system outcomes in different ways, and in particular when separating resilience into depth and recovery.

When faced with a repeated direct environmental shock pattern, we find decreases in both depth and recovery with each shock in constrained systems (with the latter failing to compensate for the former), reflective of an approaching system collapse through degradation. Conversely, both depth and recovery increase in unconstrained systems (with priming policies allowing recovery to even exceed pre-shock levels). Through disentangling the interconnected parts of the food system, we highlight market and finance mechanisms as effective in restricting shock impacts to production outcomes (i.e., livelihoods are only minorly impacted, whilst environmental outcomes are unaffected), both via price mechanisms and cooperatives' absorption of disruptive impacts. Distributionally, we find direct environmental shocks tend to affect all farmer types equally in terms of depth, but commercial small-holders are most "volatile", being able to recover / adapt (as a population) due to small-scale land turnover, though are also then vulnerable to subsequent shocks if overleveraged. Further, we find an example debt forgiveness policy pushes the behaviour of an otherwise constrained system towards that of an unconstrained system, in relation to resilience responses to *this shock type*, as it lessens degradation rates (via lessening practice change constraints and short-term earnings losses impacts). We note that recent debt forgiveness policies directed at farmers (see e.g., the debt forgiveness package contained within the US Inflation Act, 2022) are likely to be helpful in this regard.

When a system is faced with a repeated general system shock pattern, we instead find general decreases in depth with each shock across both production and livelihoods, but do so due to *a lack of adequate recovery*. When broken down distributionally, we find these effects are driven by **commercial large-holders**, due to their reliance on healthy labour markets to operate large farms, and the dynamics of down-sizing / up-sizing cycle rates leading to **gradual absorption of land by smaller operations**. This finding is moderated by the geospatial arrangement of large holders and small holders, and the capacity of large holders to engage in increased mechanisation solutions. Importantly, this finding illustrates the multi-faceted nature of food systems outcomes, wherein – if concerned primarily with livelihoods – we find a relatively positive picture of increased equality across farmers (i.e., small-holders increase in number and average farm-size, whilst large-holders reduce holdings). However, if our primary concern is long-term production, then the "targeted" loss of commercial large-holders has a disproportionate impact on food production, given their 1) operating scale, and 2) increased capacity to adopt new practices. Unlike direct environmental shocks, as one of the central drivers of these resilience effects is labour availability, policies that increase cash-flow or incorporate debt forgiveness are relatively ineffective.

Reversals undermine long-term success. Although the intent of the policy reversals tested is to increase production levels following a perceived decrease, we find not only that this short-term goal is never achieved, but that the act of reversing can harm long-term production via compromised behaviour change. More precisely, reversing a policy intended to promote regenerative practices in favour of agnostic production leads to lower rates of uptake, not just directly re: soil quality outcomes, but risks undermining belief in the longevity of future policy proposals among stakeholders. Moreover, reversals intending to return to / exceed previous production levels fail to account for continued environmental degradation in the interim.

Reversals carry risks not just in response to direct environmental or general system shocks.

Policy ambition directly impacts the temptation to reverse. Weaker policies (e.g., standard regenerative policies) being both less disruptive and less effective, do not produce a short-term noticeable "change" (i.e., production loss), but instead through continued insufficient rates of change (and consequent ongoing degradation) result in a gradually inevitable "last-ditch" reversal in the long-term. The two additional harms associated with this being 1) such late-stage reversals may come too late given the limited time-scales in resolving current food system pressures, and 2) the insufficiently ambitious policy may provide a false sense of security that masks the need for further action. Conversely, we find that stronger policies (e.g., priming policies) are initially more disruptive (due to short-term production losses following large-scale switches to regenerative practices), but *only in the short term*, highlighting the importance of policy commitment mechanisms (e.g., an equivalent assessment to the value of interest rate commitments, see Barro & Gordon, 1983). More broadly, this highlights the importance of diagnostic accuracy in both determining sufficient policy ambition, but also in determining the causal mechanisms behind system changes. For example, we also find that system constraints can increase the likelihood of reversals, though this is the product of poor awareness of what needs to change. If *additional* policies are implemented (e.g., debt forgiveness), then not only are livelihood losses stemmed, and likelihood of future reversals lowered, but production can begin to see gains through priming policy uptake now being enabled.

In summary, we find different patterns of resilience across shock types, system type, scale, and chosen outcome. Moreover, we find interactions between these dimensions and land re-distribution feedbacks, (in)equality, market forces, and pressures on policy-makers. Taking these findings together, it again emphasises the importance of accurately identifying your target system, not only in terms of recognised constraints and farmer archetype mixtures, but also in terms of likely shock type patterns. All of these will affect both general predictive efficacy and the design and implementation of effective policy, including concerns regarding who it is likely to benefit, who is likely to be made more vulnerable, and who is more likely to be receptive of transition, and when. Finally, we highlight the importance of gauging policy ambition accurately, and accompanying it with sufficient commitment mechanisms to prevent deleterious policy reversals. Solid causal understanding is required to differentiate between "healthy" and "unhealthy" system change (e.g., short term "dips" due to practice shifts, vs. locked in continued degradation), such that policy monitoring and adjustment as conditions change (e.g., a shock occurs) is best informed to continue and enhance a consistent transition process.

Acknowledgements

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Method [NOTE: This model description is primarily co-opted from Pilditch et al., *under review*, and is therefore subject to change.]

The TELLUS model is built in Netlogo (6.2.2), with simulation wrappers written in python. The model, all simulation wrappers and descriptions are made available in the Supplementary Information.

6.1. Model Description

The current version of the TELLUS model embeds a farm system within a 100 x 100 hectare 2D space (consisting of 10,000 "patches", each representing 1 hectare), with 20% of available land (2,000 hectares) taken up by active farmland. At baseline, average productivity of a hectare of farmland is assumed to be 4 tonnes per year (e.g., of wheat), and the soil quality is assumed to be 45*u* (an amalgam unit measure, where 0 = completely degraded, and 100 = completely regenerated/healthy). The population of farmers are allocated onto this 2D landscape, according to specified characteristics (e.g., farm size, capital, current farming practices, psychological profile, etc.), and the surrounding value chain (e.g., buyers, suppliers, cooperatives) is distributed across the system in accordance with the density of farmers across the 2D space.

Each discrete time-point in the model reflects a complete harvest-year, within which: The farmland ecology is updated in accordance with the practices enacted upon it. The farmers update their knowledge state given their own experience, observations, and information communicated to them, before making a number of relevant, interrelated decisions (e.g., selling produce up the value chain, acquiring new inputs, deciding on farming practices, down-sizing/up-sizing/selling/buying/renting land). Suppliers, buyers, and cooperatives, make decisions about pricing, product sales, contracting, and possible exit decisions, based on their updated experience each year. New farmers and value chain members can also enter the system each year, depending on current market conditions and land availability. Each simulation run follows a 2-year 'spin-up' period, and runs for a further 30 years (time-points).

Full details of the model setup and running protocols, are outlined in the Supplementary Information, along with a complete description of all parameters and manipulations, and the python simulation scripts for running the model.

6.2. Data Processing

At each time-point within the TELLUS simulation, a host of variables are collected and stored. For each permutation of the model, 20 simulations are run and their results are averaged for each time-point, with variance in those results stored as corresponding standard deviations. These variables include the total amount of food produced by farmers in the system that year (recorded as a percentage of the baseline amount of food produced), the mean soil quality of currently farmed land that year, and the number of farmers active in the system that year. In addition, though not shown here for reasons of brevity, these variables can be broken down by farmer archetype, such that more in-depth questions can be investigated (e.g., changes in soil quality among subsistence small-holders), and supplementary system variables are also recorded as time-series (e.g., price changes, practice choices, active contracts, subsidy expenditures). Note we do not cut-off the period of adjustment at the beginning of the simulation period where factors like imposed system constraints may substantively affect farmers. This "burn-in" period is not excised for two reasons: First, the complex nature of the farming system means there is no immediately reachable equilibrium state to define the end of "burn-in". Second, in removing this initial period of adjustment, we risk obfuscating the true impact of the constraints we are testing (i.e., part of their effect is arbitrarily removed).

Details on data processing (notably the scripts written in R to process simulation outputs) can be found in the Supplementary Information.

6.3. Policies

Here we introduce our selection of policies reported in the main text, and the rationale behind them. Full details of these policies, as well as a wider selection of policies not reported here may be found in the online supplementary materials.

No Policy. The purpose of the "No Policy" condition is to act as a baseline against which other policies may be compared. Throughout this condition, no taxes, subsidies, or other policy levers are applied at any point.

Regenerative Subsidy. The "Regenerative Subsidy" condition serves as a representation of subsidy policies intended to act as a "carrot" that persuades farmers towards less carbon-intensive / regenerative farming practices (see e.g., discussion of environmental land management schemes and tying agricultural subsidies to regenerative goals[2]). As with the carbon tax policy above, this is a fixed amount (here \$100) applied additively per regenerative practice, per hectare. Thus, at a maximum a farmer engaging in entirely regenerative practices will acquire a subsidy of \$600 for each hectare farmed in this way. This policy begins at year 6 of the simulation (post system burn-in), and remains throughout. When active, the subsidy is available to all farmers, irrespective of commercial or subsistence purposes, geographical location, a priori awareness, or any other factors.

Priming Policy Bundle. The purpose of the priming policy bundle is to take advantage of temporal dynamics found within complex systems, notably where behaviour is highly interdependent (e.g., how one farmer acts is informed by the previous actions of their peers[8]). The intention with this policy is to introduce strong, early incentives for engaging in regenerative practices, which then taper off as intertemporal dynamics take over. Put another way, the subsidy is used to reach a "critical mass" of uptake as fast as possible, after which social, cultural, and market dynamics assist in pushing the uptake towards saturation.

To provide this initial prime, a regenerative land-based subsidy of \$500 per regenerative practice per hectare is introduced that tapers down to 0 over 13 years (in \$100 increments every few years). Once this prime has tapered, an increasing carbon tax on non-regenerative practices is introduced, starting at \$10 per non regenerative practice per hectare, rising to \$200 over the next decade. This latter component serves two purposes: First, it is intended to dissuade back-sliding, but without the problems associated with an immediate carbon-tax (e.g., late changers are increasingly unable to afford to invest in change). Second, any revenues generated can help offset the cost of the prime subsidy, and/or fund subsequent initiatives.

Along with this incentives policy, the remaining bundle introduces additional policy levers to further encourage regenerative practice uptake, beyond the efficacy of a regenerative subsidy alone. These additional policy levers are implemented contemporaneously with the introduction of the priming subsidy, and are as follows:

Market: Buyers. The previously externalised costs associated with the non-regenerative production of food is introduced as an increasing percentage tax on buyers trading in non-regenerative goods (starting at 10%, increasing a further 10% every 3 years, rising to 80%).

Market: Cooperatives. Cooperatives are increasingly incentivised to facilitate regenerative production among farming members. This is achieved by gradually adjusting cooperative focus towards regenerative buyers, and therefore being increasingly less willing to sell-on member products to non-regenerative buyers. This is signalled both to (potential) farming members, and surrounding buyers.

Market: Inputs. One of the non-regenerative practices employed by farmers is the use of artificial inputs (e.g., pesticides). Consequently, one policy lever intended to reduce this is to ban these inputs[3]. Here this is implemented by preventing suppliers from selling such inputs, entirely preventing access to all farmers.

Taken together, these market policy levers are intended as a countermeasure to price and market-access based decelerating and backsliding forces on the rates of regenerative practice uptake (e.g., non-regenerative product price increasing as supply reduces, tempting farmers back to non-regenerative practices).

Information: Advice Outreach. Possessing the requisite knowledge is a necessary precondition for implementing a new farming practice. This has been acknowledged as a potential barrier to change[4], and thus is a candidate for policy intervention. Accordingly, this policy lever focusses on disseminating the required knowledge for farmers to make informed decisions to implement regenerative practices. Here this is achieved through Government Extension Agents (GEAs) and agronomists shifting to focus entirely on the provision of regenerative practice information. This shift necessarily *precedes* subsidy/tax and market interventions by several years.

Information: Online/Internet Use. The use of the internet has been noted as a useful tool for farmers to share their experiences and learn about regenerative practices. However, this has notably occurred primarily among larger commercial operations in the developed world[5]. Here we add a policy lever that focusses on enabling and encouraging the use of the internet among all farmer archetypes to share and learn about new practices. Although search and sharing behaviours are set to increase over time across all farmer archetypes, this use is expected to be more comprehensive among wealthier, large commercial farmers, than among small-holders who may have higher rates of technological barriers (e.g., no internet access and/or computer/phone technology).

Retirement. Early retirement policies have been argued as a useful way to shift farming populations towards younger, more innovation embracing new farmers (see e.g., early retirement policies in Finland[6] and Spain[7]). Here we implement such a policy lever, wherein the mean retirement age is reduced from 65 to 50 years old, and then gradually increasing by 5 years every 6 years, reaching 70 years old by 2048.

6.4. System Archetypes

System Archetypes. In the real world, the mixture of farmer archetypes (e.g., commercial small-holders vs commercial large-holders) differs considerably by region. As outlined in the Supplementary Information, we tested two regional archetype mixtures: *majority large-holder* (more typical of "developed world" farming regions, with approx. 70% of farmland operated by commercial large-holders, the remainder split evenly between subsistence and commercial small-holders) and *majority small-holder* (approx. 70% of farmland is operated by commercial or subsistence small-holders, with the remaining farmland operated by commercial large-holders, reflecting typical mixtures in "developing world" regions). These mixtures were not found to be substantively impactful, and so for clarity are not reported in the main text. This lack of substantive impact is likely due to our separation of the economic and physical constraints (often correlated with these archetypes) for orthogonal manipulation. In this way we have been able to determine generalised causal characteristics whose presence (regardless of "developed" vs "developing" world classification) typify deleterious system and farmer projected outcomes.

Appendix

Appendix A

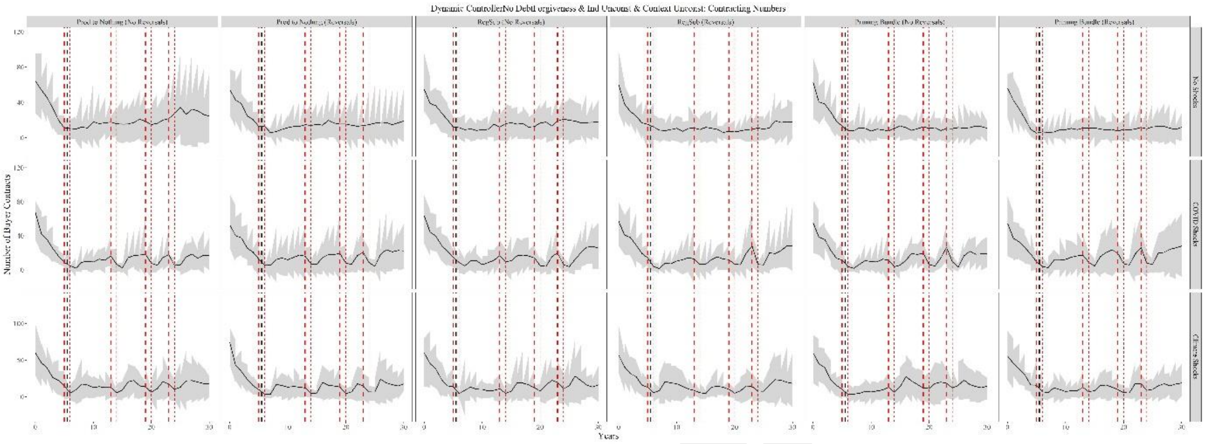

Figure A1. Number of production contracts, using mean values across a 30-year period. Economically unconstrained farmer scenario and majority large-holder system is illustrated. Policy scenarios are shown across facet columns, and shock conditions are shown across facet rows. Ribbons reflect +/-1 S.D.

Appendix B

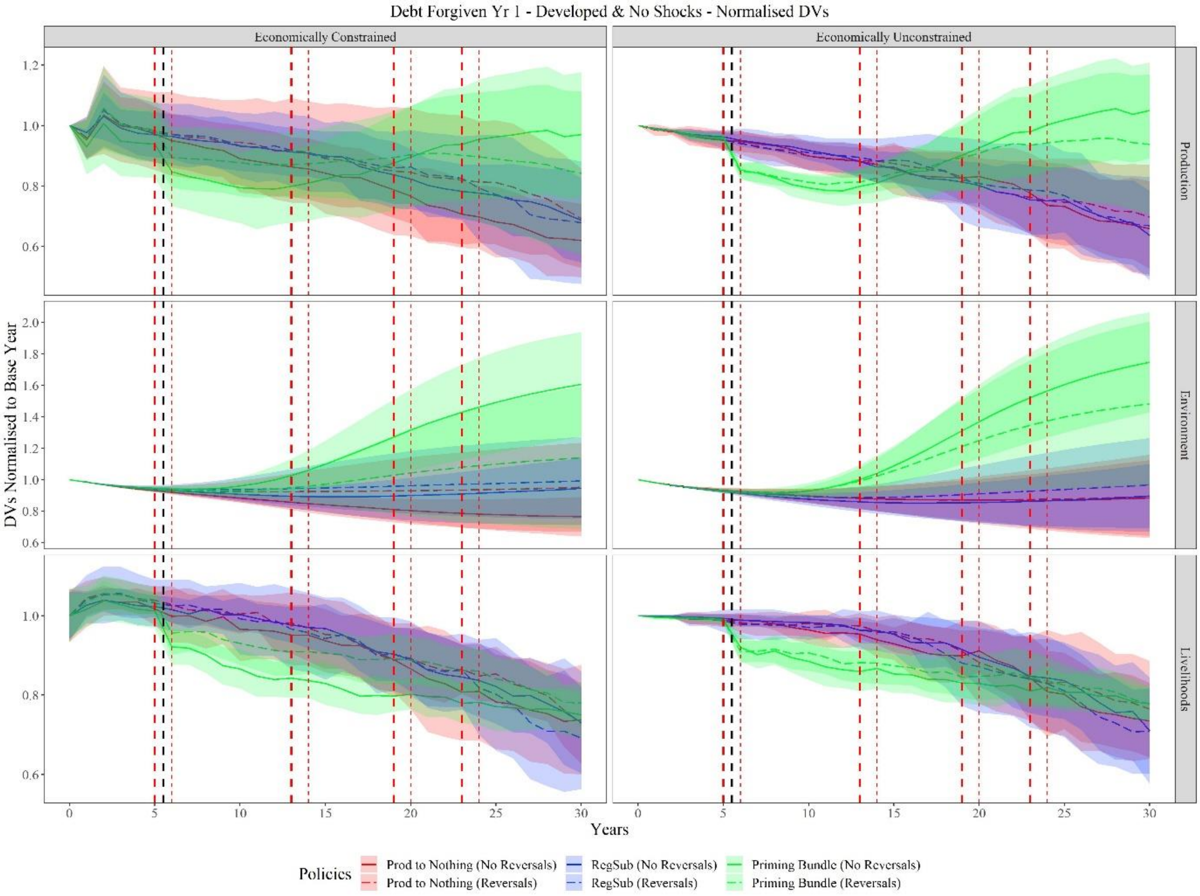

Figure B1. Policy and policy reversal impacts under no shocks condition (at red dashed vertical lines) on total food production (top row), average farmland soil quality (environment; middle row), and number of farmers (livelihoods; bottom row), using mean values across a 30-year period, normalised to baseline values. ***All farmer debt forgiven in year 1****. Economically constrained (left-hand column)* *and unconstrained (right-hand column) farmer scenarios are tested, and majority large-holder system is illustrated. Policy scenarios shown are: no subsidy (red), a fixed subsidy for regeneratively farmed land (blue), a "priming" regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information campaign (green). Solid line-types = no reversals; dashed line-types = reversals. Ribbons reflect +/-1 S.D.*

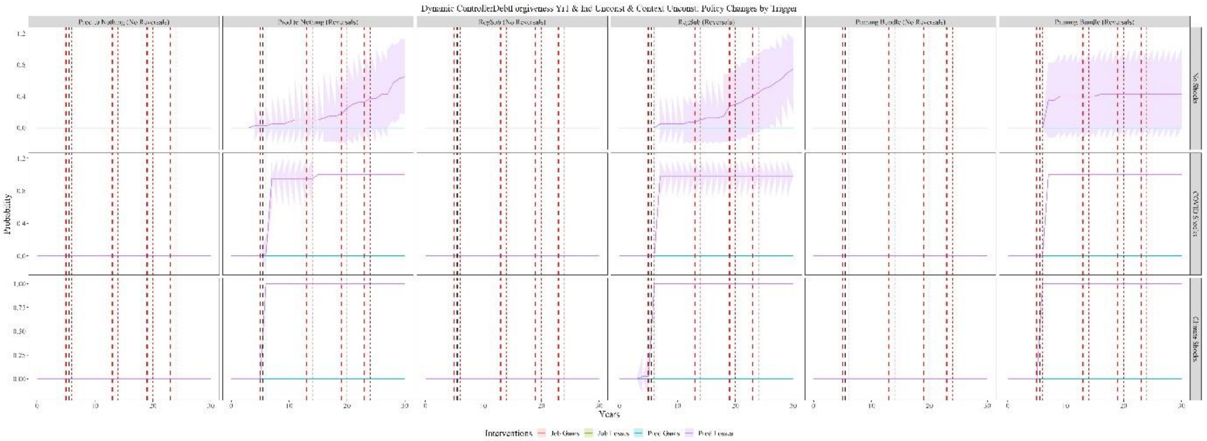

Figure B2. Likelihood of policy reversal, using mean values across a 30-year period. ***All farmer debt forgiven in year 1****. Economically unconstrained farmer scenario and majority large-holder system is illustrated. Policy scenarios are shown across facet columns, and shock conditions are shown across facet rows. Ribbons reflect +/-1 S.D.*

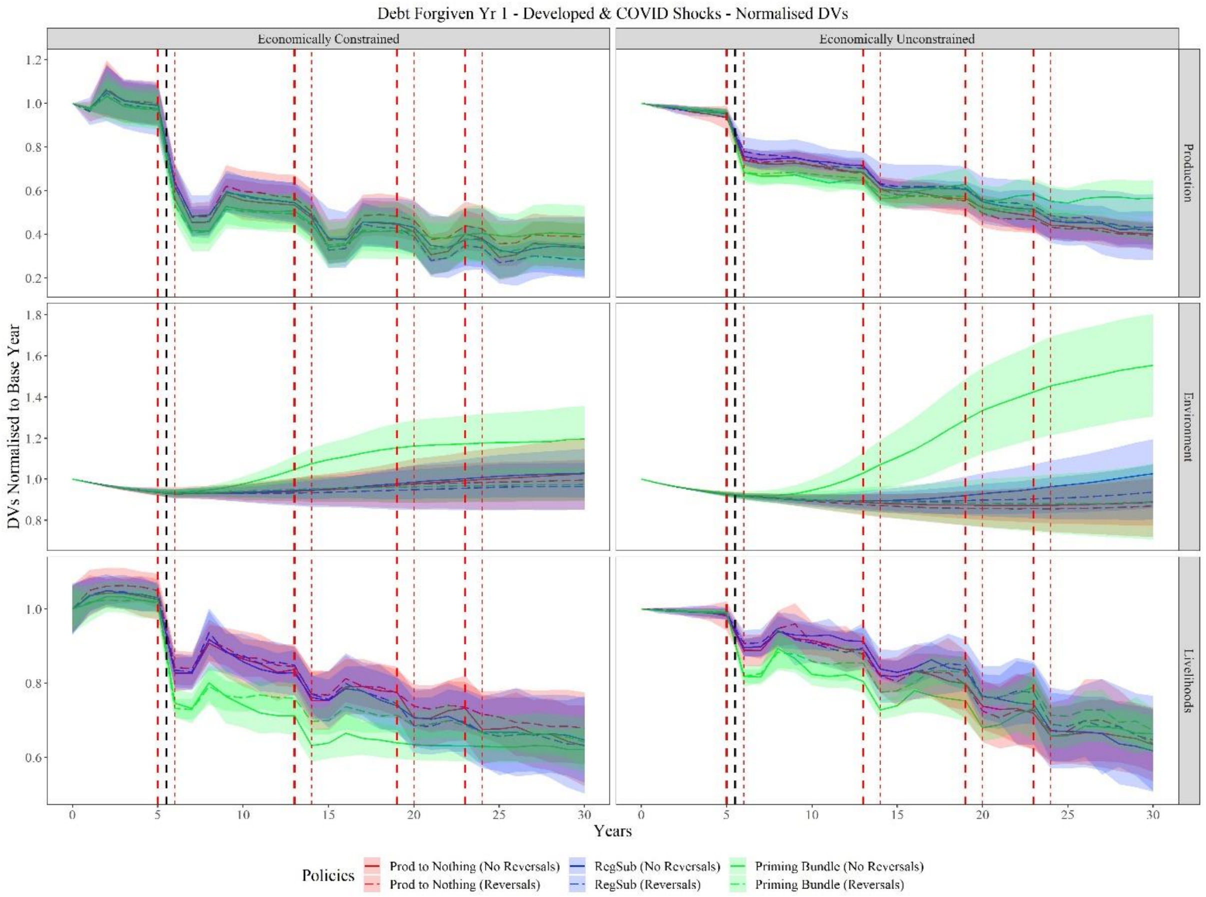

Figure B3. Policy and policy reversal impacts under COVID shocks condition (at red dashed vertical lines) on total food production (top row), average farmland soil quality (environment; middle row), and number of farmers (livelihoods; bottom row), using mean values across a 30-year period, normalised to baseline values. ***All farmer debt forgiven in year 1****. Economically constrained (left-hand column) and unconstrained (right-hand column) farmer scenarios are tested, and majority large-holder system is illustrated. Policy scenarios shown are: no subsidy (red), a fixed subsidy for regeneratively farmed land (blue), a "priming" regenerative farmland subsidy that starts high and tapers gradually to 0, then into a carbon tax on non-regeneratively farmed land plus a policy bundle including regenerative product incentives for buyers and cooperatives, an artificial pesticide ban, and a regenerative farming information campaign (green). Solid line-types = no reversals; dashed line-types = reversals. Ribbons reflect +/-1 S.D.*