

# From ecological interaction vulnerability to multiple breadbasket failure: a cross-domain material-transmission framework

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## Research Article

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# Abstract

Mechanisms linking ecological interaction vulnerability to agronomic production and downstream food-system stress are dispersed across largely separate literatures, leaving their combined implications for food-dependent social systems poorly understood. This gap is addressed through a structured qualitative comparison of published cases spanning mutualistic and soil communities, agroecosystems, production regions and human systems. The analysis evaluates the applicability of transition mechanisms proposed in regime-shift research, distinguishes direct observations from modelled and author-inferred transitions, and derives testable expectations about downstream food-system stress. Structural properties such as connectance, redundancy and response diversity are treated as system-specific; what crosses boundaries is a material function or disturbance, not an unchanged network property. The synthesis indicates that vulnerability in pollination and soil functions may constrain agroecosystem compensation, while crop-portfolio concentration may reduce response diversity under shared climatic forcing. It therefore proposes the hypothesis that antecedent ecological and crop response diversity moderates the severity and persistence of production losses, influencing the risk of multiple breadbasket failure. Resulting food-system shocks may then affect households, markets and institutions through system-specific mechanisms. Adjacent links are classified as domino effects, hidden feedbacks or driver sharing, yielding a transparent framework with independently falsifiable transitions.

## Introduction

Regime shifts, defined as large, abrupt, and persistent transitions in the structure and function of ecological systems, have historically been studied one system at a time (Scheffer, 2009). Here, collapse denotes the persistent loss of the defining structure, function or identity of a specified system; because that diagnosis depends on the system identity evaluated, the referent must be stated explicitly and competing mechanisms considered. A large ecological change is not, by itself, evidence of social collapse (Cumming & Peterson, 2017; Newton et al., 2024). This within-system framing has produced complementary structural and dynamical toolkits: properties such as connectance, nestedness and modularity characterise community architecture and stability (Bascompte & Jordano, 2007; Thébault & Fontaine, 2010), while rising variance and critical slowing down may precede critical transitions (Scheffer et al., 2009, 2012). Carpenter et al. (2011) demonstrated these signatures experimentally in a whole-lake manipulation, detecting the statistical precursors of a trophic collapse before the collapse itself became visible in the fish community. This body of work established that regime shifts, although abrupt in their final expression, may be preceded by detectable changes in system dynamics. Using a generalised modelling approach, Lade et al. (2013) showed that explicit human behavioural dynamics can determine whether a social-ecological regime shift occurs and outlined possible early-warning signals for the modelled transition under structural uncertainty.

A separate and more recent line of enquiry has asked whether regime shifts in different systems (ecological communities, agroecosystems, or social-ecological systems) can interact, rather than

occurring as independent events. Rocha et al. (2018) addressed this question directly, analysing thirty documented regime shifts as networks and showing that 45% of pairwise combinations exhibited a plausible structural interdependence. They distinguished two mechanisms of interaction: domino effects, in which a transition in one system creates a one-way dependency that increases the likelihood of a transition in another, and hidden feedbacks, in which two systems are coupled bidirectionally such that each transition reinforces the other. Both mechanisms were distinguished from the simpler case of driver sharing, analogous to the 'common cause' interdependency identified in critical-infrastructure research (Rinaldi et al., 2001), in which systems appear correlated only because they respond to a common external stressor rather than to one another. This distinction, building on earlier work on interacting regime shifts within single ecosystems (Brock & Carpenter, 2010), provides the conceptual vocabulary this article uses throughout.

A parallel development has traced ecological reorganisation into human economies through material dependence. Gregr et al. (2020) combined empirical ecological evidence with trophic modelling to estimate how sea otter recovery could redistribute economic returns from ecosystem services. The study provides a traceable, model-based material pathway from predator–prey reorganisation to human economic consequences without implying that ecological and social subsystems share mechanisms, agency or trajectories (Newton et al., 2024). What remains insufficiently specified in this literature is how *changes specific to one agronomic or ecological system* (for example, pollinator decline in one crop system) are transmitted across ecological, agricultural, food-system and human-system boundaries without treating those systems as mechanistically equivalent. A companion article (Stumpf-Biró et al., 2026) examines one segment of this problem by proposing community embeddedness, defined as the density of realised cooperative ties among individuals, households and local organisations, as a candidate domain-specific structural property of human cooperative networks and by deriving testable hypotheses for its erosion from ecological early-warning theory.

The novel contribution is twofold. First, the analysis integrates and reclassifies heterogeneous evidence from otherwise disconnected literatures using a common distinction between within-system architecture and cross-system material transmission. Second, it generates a specific falsifiable hypothesis: antecedent ecological and crop response diversity moderates the severity and persistence of production loss under shared climatic forcing. This is the primary testable claim linking the analysed transitions into a single account. Here, domain denotes an analytically distinct system class – an ecological community, agroecosystem, production region or human system – with its own state variables and generative mechanisms. Material coupling can transmit disruption between domains without making them mechanistically equivalent. This article develops that proposition into an explicit, testable cross-domain transmission framework.

In this framework, biodiversity is treated not only as species richness but as the diversity, organisation and substitutability of realised interactions and ecological functions within communities (Valiente-Banuet et al., 2015). At the base, anthropogenic pressures alter the abundance, distribution, phenology and realised interactions of species in mutualistic and soil communities; where effective partners or

functions are poorly substitutable, these changes can reduce the ecological functions available to agroecosystems. Such functional losses can constrain agroecosystem compensation in a global food system that has become more homogeneous and concentrated around a small number of dominant crops, creating structural vulnerability to synchronised failure across geographically distant production regions under compounding climatic stress, a phenomenon known as multiple breadbasket failure (Anderson et al., 2019; Gaupp et al., 2020). Multiple breadbasket failure is then treated as a material disturbance transmitted into human systems, where it acts on domain-specific economic, institutional and cooperative mechanisms, including the community-embeddedness architecture addressed in the companion article, rather than as the continuation of the same ecological network.

Within-domain architecture and cross-domain material transmission are treated as separate analytical objects. Connectance is used here as the proportion of realised interactions among all possible interactions within a defined community; redundancy as the number of functionally equivalent partners or pathways available should one be lost; and response diversity as the range of distinct responses to disturbance among components that share a function. In this analysis, claims about network properties require explicitly defined interaction data and are not inferred from aggregate abundance or biomass. Topology-based food-web analysis can identify directional asymmetries among interactions that non-network indicators do not themselves encode (Hidas & Jordán, 2025). Connectance, redundancy and related network properties are used only within a domain where the relevant realised relationships are defined or directly measured; species interactions and human cooperative relationships are governed by fundamentally different mechanisms, the former by evolved behavioural and physiological traits, the latter by intention, institutions and reflexive social choice, and no shared measurement is assumed between them. Across domain boundaries, the analysis instead codes the material function or disturbance transmitted to the receiving system, for example a pollination service lost, a production volume reduced, or a food price increased, not the transfer of an identical network property. This separation follows a broader methodological caution about transferring regime-shift concepts from ecological to social systems. Kull et al. (2018) distinguish descriptive from normative uses of the concept and material from conceptual change, while emphasising the multiplicity of perspectives, power relations and historical contingency in social systems. This rule is implemented in the Methods, evidence matrix and classification of adjacent transitions (Biggs et al., 2021; Kull et al., 2018; Newton et al., 2024).

## Methods

This study uses a structured qualitative comparison of a purposively assembled corpus of published ecological and social-ecological cases. The published cases constitute the qualitative dataset, and the unit of analysis is a reported or author-inferred transition linking a disturbance, an affected interaction or function, a receiving system and a consequence. The analytical contribution is a new reclassification and cross-domain comparison of these cases, not a comprehensive synthesis of the underlying fields. Directed qualitative content analysis and the framework method were used because the initial categories were derived from regime-shift and network theory while allowing additional mechanisms and counter-

mechanisms to be recorded where evidence did not fit those categories (Gale et al., 2013; Hsieh & Shannon, 2005).

A purposive corpus was assembled from foundational regime-shift, community-network, ecosystem-service, agroecosystem and multiple-breadbasket literatures, using forward and backward citation tracking from key theoretical sources (Rocha et al., 2018; Scheffer et al., 2009, 2012; Bascompte & Jordano, 2007), supplemented by the purposive identification of additional studies on multiple breadbasket failure and agroecosystem diversity. Sources were retained when they provided (i) an observed ecological interaction or community function, (ii) an identified anthropogenic or climatic pressure, (iii) evidence relevant to transmission between adjacent cascade stages, or (iv) a clearly specified counter-mechanism such as functional substitution, adaptive response or asynchronous production. Opinion pieces and institutional reports were used only for contextual or policy framing, not as primary support for ecological mechanisms. This corpus was assembled purposively rather than through a systematic, database-level search protocol; the implications of this choice are addressed as a limitation in the Discussion.

Each source was coded for domain and scale; the domain-specific node, unit or focal species; the domain-specific interaction or dependency; the directly observed variable; the within-domain mechanism; the material output or disturbance transmitted across the domain boundary; the receiving-domain variable; evidence type; alternative explanation; and, where applicable, a falsifying or interrupting mechanism. Evidence status distinguished direct observation of an interaction or regime shift from population or biomass change, habitat or soil degradation, crop-portfolio concentration, modelled climatic synchronisation and author-derived inference. Adjacent transitions were classified as domino effects, hidden feedbacks or driver sharing following Rocha et al. (2018); mixed classifications were permitted where mechanisms co-occurred. The resulting case-level synthesis is presented in Table 1; the sources supporting each case are cited in the corresponding Results paragraphs. Evidence level was classified as demonstrated (direct observation of the focal transition), supported (indirect, associational or model-based evidence consistent with the transition), hypothesised (an author-derived transition not directly tested) or boundary (a case retained because it did not meet the evidence threshold).

Table 1

Summary evidence matrix for the proposed cross-domain cascade from interaction change to human-system disruption. Cases are numbered for reference; case 7 is retained as a precedent rather than a sequential step in the cascade (see Results).

| Case                                                                                                                                                                                                                                                                                                                       | Focal system                                                | Interaction                     | Observed                                        | Inference                                    | Status                                                      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------------------------|-------------------------------------------------|----------------------------------------------|-------------------------------------------------------------|
| 1                                                                                                                                                                                                                                                                                                                          | Plant–pollinator communities, including <i>Bombus</i> spp.  | Pollination service             | Link/function loss; range, biomass decline      | Decline may remove key interactions          | Direct link; indirect participant support                   |
| 2                                                                                                                                                                                                                                                                                                                          | <i>Dolichoderus bidens</i> – <i>Protopolybia emortualis</i> | Protective ant-wasp nesting     | Asymmetric co-occurrence benefit                | Low substitutability raises vulnerability    | Association only; feedback unconfirmed                      |
| 3                                                                                                                                                                                                                                                                                                                          | <i>Ficus</i> spp.-Agaonidae fig-wasp pair                   | Obligate pollination            | High specificity, mutual dependence             | Partner loss removes the function            | Direct dependency; no temporal loss observed                |
| 4                                                                                                                                                                                                                                                                                                                          | Soil biota (fungi, bacteria, fauna)                         | Nutrient cycling, decomposition | Soil degradation; food-web function documented  | Land-use pressure may disrupt interactions   | Hidden feedback plausible; unmeasured                       |
| 5                                                                                                                                                                                                                                                                                                                          | Crop systems and varieties                                  | Genetic and landscape mix       | Rising similarity of food supplies              | Simplification reduces compensatory capacity | Amplification, not connectance loss                         |
| 6                                                                                                                                                                                                                                                                                                                          | Major breadbasket regions                                   | Climate-linked production       | Synchrony; concurrent-failure risk              | Ecological state may shape shock severity    | Confirmed driver; moderation a hypothesis                   |
| 7                                                                                                                                                                                                                                                                                                                          | <i>Enhydra lutris</i> , urchins, kelp, fisheries            | Marine trophic cascade          | Ecological change; modelled ecosystem effects   | Material transmission is modelled            | Empirically grounded domino precedent                       |
| 8                                                                                                                                                                                                                                                                                                                          | Households, markets, institutions                           | Food availability and trade     | Modelled food-supply effects; price-unrest link | Severe shocks may erode social capacity      | Published downstream evidence; embeddedness effect proposed |
| Evidence status distinguishes direct observation of species, interactions, functions or production outcomes from author-derived inference across adjacent domains. Population or biomass decline, soil degradation and crop-portfolio concentration are not coded as connectance loss unless realised links were measured. |                                                             |                                 |                                                 |                                              |                                                             |

To preserve an explicit distinction between evidence and synthesis, no decline in abundance, biomass, soil condition or crop diversity was coded as connectance loss unless realised interactions or network

links were measured directly. The matrix was also reviewed for non-supporting boundary cases and alternative pathways, including functional replacement, adaptive evolution, management substitution and production asynchrony (Chaparro-Pedraza et al., 2021; Cumming & Peterson, 2017; Mehrabi & Ramankutty, 2019). Two domains were never coded as sharing a propagated connectance value; only documented or explicitly hypothesised material transmission was coded across a domain boundary. One case, the protective nesting association between two social insects addressed below, is retained explicitly as a non-supporting boundary case. It illustrates a low-substitutability topology but did not meet the evidence threshold for demonstrated reciprocal feedback.

This analysis refers to the companion article (Stumpf-Biró et al., 2026) only as a proposed human-system architecture; it neither treats that architecture as empirically established nor re-derives the article's propositions. Every source used in the present qualitative comparison is specified here.

No primary field or experimental data and no new numerical network metrics were generated. The analytical outputs are the case reclassification, evidence matrix, transition typology and falsifiable moderating hypothesis.

## Results

### Interaction vulnerability in mutualistic networks

Mutualistic networks can be described by connectance, nestedness, partner specificity and interaction redundancy; their responses to disturbance depend not only on species richness but on which realised interactions and functions are retained (Bascompte & Jordano, 2007; Latty & Dakos, 2019). The cases below distinguish direct temporal interaction change from pressure on network participants and structural dependence; only the historical comparison by Burkle et al. (2013) directly documents realised interaction and functional change through time.

Case 1 concerns plant–pollinator communities, which include flowering plants linked to bees, hoverflies and other flies, butterflies, moths, beetles and wasps, with partners differing in visitation frequency, effectiveness, phenology and substitutability. Across a 120-year comparison in Illinois, Burkle et al. (2013) documented losses of bee species and plant–pollinator co-occurrences together with lower visitation rates and floral fidelity, providing direct temporal evidence of interaction and functional change. Climatic range contraction in bumblebees (*Bombus* spp.) and declining flying-insect biomass demonstrate pressure on potential network participants (Hallmann et al., 2017; Soroye et al., 2020), but neither study directly measured realised link loss or connectance; both are therefore coded as pressure on network participants, not as observed connectance decline. Network-level evidence is available elsewhere in this system. Using reconstructed pollination networks across the Brazilian Atlantic Forest, Pereira et al. (2022) found that connectance and nestedness were positively associated with forest cover. This provides cross-sectional, model-assisted evidence of habitat-associated network simplification, not direct temporal observation of link loss. Network theory nevertheless predicts disproportionate functional effects when disturbance removes highly connected or poorly replaceable

partners, and pollination systems may show threshold responses and cascading failures when compensatory interactions are insufficient (Bastolla et al., 2009; Latty & Dakos, 2019).

Case 2 involves the protective nesting association between the arboreal ant *Dolichoderus bidens* and the swarm-founding social wasp *Protopolybia emortualis* in French Guiana. The wasp benefits from ant aggression towards potential predators and army-ant raiders, but the cited studies do not demonstrate symmetrical fitness benefits or reciprocal feedback (Corbara et al., 2018; Servigne et al., 2020). It is therefore retained as a non-supporting boundary case, an asymmetric, low-substitutability association that does not meet the threshold for a demonstrated hidden feedback.

Case 3, obligate pollination mutualism between fig trees (*Ficus* spp.) and their species-specific fig wasp pollinators (family Agaonidae), represents the structural limit of minimal substitutability rather than an observed instance of connectance erosion. Each fig species is typically pollinated by one, or a small number of, co-adapted wasp species, and neither partner can reproduce without the other (Cook & Rasplus, 2003). This one-to-one dependency leaves the interaction with effectively no redundancy. The local loss of the wasp partner is structurally equivalent to the loss of the interaction itself, independent of the abundance of either species considered separately, and the case demonstrates a dependency structure, not a temporally observed network-level loss.

Together, these cases distinguish three routes to interaction vulnerability: diffuse plant–pollinator networks exposed to participant decline or phenological decoupling; an asymmetric protective association with low partner substitutability; and obligate fig-wasp pollination in which partner loss directly removes a reproductive function. They therefore contribute different evidence types rather than points on a single measured gradient of connectance erosion. These cases indicate that vulnerability to interaction loss is not uniform. Its consequences depend on partner specificity and functional redundancy, which shape the material function transmitted to the agroecosystem domain.

### **Interaction vulnerability in soil biotic communities**

Case 4 turns to soil communities, which contain plants, arbuscular mycorrhizal fungi, bacteria, saprotrophic fungi, protists, nematodes, earthworms, Collembola, mites, predators and pathogens connected by mutualistic, trophic, competitive and habitat-modifying interactions. These communities regulate nutrient acquisition, organic-matter transformation, soil aggregation, water retention, plant defence and pathogen pressure. Although many components are difficult to monitor routinely, their interactions can in principle be measured directly rather than inferred solely from crop yields or aggregate soil-health indices (Bardgett & van der Putten, 2014; de Vries et al., 2013).

Arbuscular mycorrhizal fungi exchange soil-derived nutrients and water for plant carbon; saprotrophic fungi and bacteria decompose organic matter; earthworms modify soil habitat as ecosystem engineers; Collembola and mites graze microbial and fungal resources; and nematodes include bacterial-feeding, fungal-feeding, predatory and plant-parasitic guilds. These organisms are neither a single decomposer guild nor functionally interchangeable, so the consequence of decline depends on which relationships

and processes are lost (Bardgett & van der Putten, 2014; de Vries et al., 2013; Smith & Read, 2008). Across European land-use systems, de Vries et al. (2013) showed that soil food-web properties explained variation in carbon and nitrogen cycling beyond that explained by land use alone, supporting a link between below-ground community structure and measurable functions.

Pressure on these soil biotic communities is documented primarily through degradation of the soil medium that supports them rather than through direct observation of changes in biotic interactions. FAO and ITPS (2015) reported that approximately one third of the world's soils were moderately to highly degraded. The FAO and ITPS (2015) assessment establishes degradation of the physical and chemical medium; it does not directly measure realised biotic links or connectance. It is therefore used here as evidence of a pressure capable of reorganising below-ground communities, not as direct evidence of soil-network erosion. This degradation, driven by erosion, compaction, salinisation, and the cumulative effects of agrochemical inputs, reduces the physical and chemical conditions on which mycorrhizal, earthworm, and microarthropod communities depend, independent of any direct pressure on the organisms themselves.

Reciprocal coupling, rather than low visibility or delayed detection, is the criterion for hidden feedback (Rocha et al., 2018). Soil-community change can affect crop performance through nutrient acquisition, decomposition, aggregation and pathogen regulation, while tillage, monoculture, compaction and agrochemical use alter the habitat and resources of soil organisms. This bidirectionality makes a hidden-feedback classification plausible, but the FAO soil-condition data alone do not demonstrate it.

### **Propagation into simplified agroecosystems**

Agroecosystems receive ecological functions from pollinator and soil communities but cannot be treated as the same network by analogy alone. Their vulnerability arises from coupled but distinct forms of simplification: loss or reorganisation of ecological interactions; reduced crop, genetic and landscape diversity; and dependence on similar management practices and input systems (Cabell & Oelofse, 2012; Dee et al., 2017).

Case 5 addresses global food supplies, which have become more similar in crop composition and increasingly dependent on a common portfolio of major crops, including wheat (*Triticum aestivum*), maize (*Zea mays*), rice (*Oryza sativa*) and soybean (*Glycine max*) (Khouri et al., 2014). Crop-portfolio concentration is not connectance loss; it reduces response diversity and potential compensation at the production level. Consistent with that distinction, greater crop diversity is associated with greater temporal stability of national harvests (Renard & Tilman, 2019). This pattern is consistent with community-ecology evidence that functional redundancy is positively associated with community stability across environmental gradients (Sadeghinia et al., 2023), supporting the treatment of crop-portfolio concentration as a potential loss of functional, not merely taxonomic, response capacity.

Case 6 focuses on major production regions. Reduced response diversity becomes consequential when production regions experience correlated climatic disturbance. Multiple breadbasket failure refers to

concurrent or near-concurrent production losses across major regions, but historical synchrony is not uniform. Within-crop production synchrony declined for several major commodities while synchrony among crops increased, with implications for aggregate calorie stability (Mehrabi & Ramankutty, 2019). Climate change is projected to increase simultaneous failure risks in major wheat, maize and soybean breadbaskets, while water scarcity and extreme heat add region-specific pressures (Caparas et al., 2021; Gaupp et al., 2019, 2020; Hasegawa et al., 2022). Extreme ENSO events may act as one teleconnected synchronising mechanism, but no current or developing event is used here as evidence that multiple breadbasket failure is occurring (Anderson et al., 2019; Cai et al., 2014).

In the terminology of Rocha et al. (2018), the correlated failure of geographically distant breadbaskets under a shared climatic driver is, considered on its own, the driver-sharing control case rather than a domino effect or hidden feedback. Production regions need not interact with one another directly for their failures to correlate, since a common atmospheric forcing is sufficient to produce synchrony. The present framework adds a separate, testable interaction. Shared climatic forcing acts on production systems whose ecological and crop-level response diversity may already be reduced. Existing breadbasket studies quantify climatic correlation and production risk, but they do not by themselves demonstrate that pollinator or soil-network erosion caused the modelled failures. This distinction is retained explicitly in the evidence matrix. ALLFED is used only to identify a risk pathway, not as primary evidence for an ecological mechanism (ALLFED, n.d.).

The inferential pathway is therefore one of compounding rather than metric transfer: interaction-dependent ecological functions shape agroecosystem compensatory capacity; crop and genetic diversity shape responses to a shared climatic shock; and production synchrony determines whether regional losses combine at breadbasket scale. The primary testable claim of this article is that antecedent ecological and crop response diversity moderates the severity and persistence of production loss under a given shared climatic forcing, not that multiple breadbasket failure itself is a novel finding. Its prediction is that, after climatic severity and management inputs are accounted for, more diverse systems experience smaller or shorter-lived production losses; evidence of no such moderation, once climatic severity is accounted for, would reject the moderating hypothesis in favour of a purely climatological account.

### **An empirically grounded, modelled cross-domain precedent**

Case 7, an empirically grounded precedent, examines a keystone-predator cascade. Gregr et al. (2020) combined observed ecological change with a trophic model to estimate the ecosystem-service and economic consequences of sea otter recovery along the eastern North Pacific. Sea otter populations, recovering from historical depletion, suppress herbivorous sea urchin populations through predation, releasing kelp forests from grazing pressure and allowing them to re-establish. This trophic release restructures the coastal food web and, with it, the productivity of several distinct ecosystem services simultaneously; the same trophic cascade that increases total ecosystem biomass and carbon sequestration also reduces the standing stock of shellfish species targeted by existing invertebrate

fisheries, producing simultaneous ecological gains and economic losses distributed unevenly across different human livelihoods.

This case is retained as a separate precedent, not as a further stage of the cascade addressed above, because it involves a different mechanism, predation rather than mutualism or crop simplification, and a different domain pairing. The model demonstrates that a change in a non-human interaction network can produce quantified, unevenly distributed economic consequences through a traceable material pathway, and that cross-domain transmission of this general kind is therefore empirically tractable. What it does not demonstrate is that social or political mediation is absent, or that the specific pathway to multiple breadbasket failure proposed in this article follows the same mechanism.

### **Material transmission into human systems**

Case 8 closes with downstream human systems. A companion article (Stumpf-Biró et al., 2026) proposes community embeddedness, defined as the density of realised cooperative ties among individuals, households and local organisations, as a candidate domain-specific structural property, and derives predictions for its erosion from the ecological early-warning literature on rising variance and critical slowing down (Carpenter et al., 2011; Scheffer et al., 2009, 2012). In that operationalisation, cooperative-tie density, overlapping support functions and the depth of cooperative bonds are treated, respectively, as within-domain architectural analogues of connectance, redundancy and mutualistic strength. That article sets out the proposed structural correspondence, its boundary conditions, measurement protocol and testable hypotheses; these are summarised here only to the extent needed to interpret the present cascade and are not re-derived.

A sustained reduction in food-system output can reduce availability and propagate through trade networks, increasing food prices and affecting economic activity (Bren d'Amour et al., 2016; De Winne & Peersman, 2021). Higher food prices can in turn increase social unrest, although the magnitude and direction of downstream effects depend on distribution, policy and institutional response (Bellemare, 2015). Each step in this chain is mediated by domain-specific economic, institutional and political mechanisms. The proposed community-embeddedness architecture is one candidate receiving-system pathway through which food-system stress may affect adaptive capacity.

The cascade addressed by this article can now be stated in full. The constituent transitions are supported to different degrees; the end-to-end cascade has not been observed as a single bounded event and is the framework's integrative, falsifiable hypothesis. Losses of ecological interactions and functions within mutualistic and soil communities constrain agroecosystem compensation; reduced response diversity within agroecosystems can amplify the severity or persistence of production losses under shared climatic forcing, increasing the risk of multiple breadbasket failure; and the resulting food-system shock acts as a material stressor on the domain-specific mechanisms of human systems, including the community-embeddedness architecture addressed in the companion article. The cases and their domain-specific evidence status are summarised in Table 1.

## Discussion

Early-warning indicators in this framework are domain-specific rather than transferable unchanged across the cascade, and this section specifies what each would require rather than asserting that a single common precursor already exists. Carpenter et al. (2011) demonstrated experimentally, within a single whole-lake ecosystem, that statistical precursors such as rising variance and autocorrelation can precede a visible trophic collapse. Whether comparable precursors are detectable across the domains addressed here depends on the availability of a routinely monitored variable specific to each domain, a condition currently met unevenly. Pollinator abundance, distribution and flying-insect biomass are indicators of pressure on potential network participants, not proxies for realised connectance; direct interaction-frequency, partner-turnover or interaction-strength time series would be needed to test network erosion directly. The same distinction applies below ground. Soil condition and yield can track habitat or function, but not connectance itself, which requires repeated observation of biotic interactions, and soil biotic connectance currently lacks an equivalent, routinely monitored proxy at the scale required for early detection. No single early-warning indicator runs unchanged across the whole cascade; each domain requires its own monitored variable, and none currently available meets that requirement at every level (Alvarez-Martinez & Miramontes, 2026; Carpenter et al., 2011; Dakos & Bascompte, 2014; Lade et al., 2013). By identifying interaction losses, declining response diversity and increasing production synchrony before cross-domain transmission occurs, the framework provides a basis for assessing adaptation readiness and prioritising monitoring across coupled ecological and food systems.

This framework complements research on multiple breadbasket failure and global catastrophic food risk by specifying a candidate ecological mechanism of vulnerability accumulation. The multiple-breadbasket literature documents observed and modelled synchrony, compound heat and water risks and projected concurrent failures (Anderson et al., 2019; Caparas et al., 2021; Gaupp et al., 2019, 2020; Hasegawa et al., 2022; Mehrabi & Ramankutty, 2019). The present framework adds a hypothesis about the ecological condition of the production systems exposed to that forcing: prior loss of interaction-dependent functions and crop response diversity may restrict compensation. This mechanism must be tested rather than inferred from the climatic studies themselves. Institutional risk sources such as ALLFED may frame consequences but are not used as primary ecological evidence. This is a claim about why vulnerability accumulates, not a competing prediction of when or where a given multiple breadbasket failure event will occur, and the framework should be read as complementary to, rather than a substitute for, the climatological and statistical literature it draws on.

Several limitations follow from the evidence base and the method used to assemble it. First, the corpus was purposively assembled rather than systematically sampled and is accordingly subject to selection bias in the cases and mechanisms included in the analysis. Second, evidence density is uneven across transitions: some links rest on direct, quantified observation, while others rest on model-based projection or cross-literature inference alone, as Table 1 reports explicitly. Third, the complete cascade has not been observed as one uninterrupted event, and no commensurable state variable exists across domains.

Connectance within an ecological community is not measured on the same scale as production diversity within an agroecosystem or cooperative-tie density within a human system; the cascade is therefore a chain of distinct, materially linked vulnerabilities rather than a single measured gradient. Fourth, abundance decline, soil degradation and crop homogenisation are not direct measures of interaction loss or connectance. Fifth, the moderating role of antecedent ecological and crop response diversity in breadbasket failure remains hypothetical rather than demonstrated. Sixth, adaptive evolution, partner substitution, diversified management, trade, redistribution and institutional response may interrupt any of the proposed transitions. The evidence matrix therefore reports direct observations, model-based projections and cross-literature inferences separately and treats alternative mechanisms as potential falsifiers (Chaparro-Pedraza et al., 2021; Cumming & Peterson, 2017).

Notwithstanding these limitations, the framework generates falsifiable expectations at each major transition, distinguishing it from a purely metaphorical use of collapse terminology. If measured interaction loss in mutualistic and soil communities coexists with stable pollination, nutrient-acquisition and pathogen-regulation functions, the first transition is weakened. If greater crop, genetic and response diversity does not moderate production loss under comparable climatic forcing, once climatic severity, irrigation, external inputs and management are accounted for, the compounding hypothesis at the agroecosystem-to-breadbasket transition is disconfirmed in favour of an account in which climatic driver sharing alone is sufficient. If the human consequences of breadbasket-scale shocks are fully absorbed by trade, redistribution and institutional adaptation, the proposed downstream transition into human systems does not occur. Each of these conditions is independently testable and independently falsifiable, rather than the framework standing or falling as a single unit.

This article links evidence on single-ecosystem regime shifts (Carpenter et al., 2011), interacting ecological regime shifts (Rocha et al., 2018) and modelled ecological-to-economic transmission (GREGG et al., 2020), while treating community embeddedness as a proposed, domain-specific receiving-system architecture rather than as a mechanistic extension of ecological connectance (Stumpf-Biró et al., 2026). It positions multiple breadbasket failure as one stage of a proposed, materially specified cascade linking ecological interaction vulnerability to disruption in human social-ecological systems. Whether each transition is best characterised as a domino effect, hidden feedback or driver sharing remains an empirical question. The longitudinal, cross-domain data needed to integrate ecological and social-ecological indicators do not yet exist in the form required to test these predictions.

## Conclusions

Community-ecology and food-system research have documented interaction vulnerability, agroecosystem simplification and breadbasket synchrony largely in separate analytical frames. This study brings those literatures into a common cross-domain analysis. It identifies a proposed sequence linking vulnerability in mutualistic and soil communities to reduced functions supporting agriculture, crop-portfolio concentration to lower compensatory capacity, shared climatic forcing to synchronised production losses, and multiple breadbasket failure to food-system shocks transmitted through markets,

livelihoods and institutions. The complete end-to-end cascade remains an integrative hypothesis rather than an observed event.

The framework does not assume that a single network property passes unchanged across systems. Instead, system-specific structural vulnerabilities shape material outputs that become disturbances to the next receiving system. Its primary testable implication is that antecedent ecological and crop response diversity moderates the severity and persistence of production losses under comparable climatic forcing. Monitoring and testing this moderation, while accounting for management, trade, institutional response and human agency, provides a tractable route for evaluating where cross-domain transmission is amplified or interrupted.

## Declarations

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### CRedit authorship contribution statement

**Balázs Stumpf-Biró**: Writing – original draft, Writing – review & editing, Conceptualization, Resources, Methodology, Investigation. **Liz Varga**: Writing – review & editing, Supervision, Conceptualization, Methodology, Validation. **Philip Tovey**: Writing – review & editing, Conceptualization, Methodology, Validation. **Danilo Brozović**: Writing – review & editing, Conceptualization, Methodology, Validation.

### Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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