Telecoupled systems are rewired by risks

Steve J. Miller[1*], Laura E. Dee[2], Meghan T. Hayden[2], Uchechukwu Jarrett[3], Amanda R. Carrico[1], Kate A Brauman[4], Eréndira Aceves-Bueno[5]

1. Department of Environmental Studies, University of Colorado Boulder, Boulder, CO, USA.
2. Department of Ecology and Evolutionary Biology, University of Colorado Boulder, Boulder, CO, USA.
3. Department of Economics, University of Nebraska-Lincoln, Lincoln, NE, USA.
4. Global Water Security Center, University of Alabama, Tuscaloosa, AL, USA
5. School of Marine & Environmental Affairs, University of Washington, Seattle, WA, USA.

*e-mail: steve.j.miller@colorado.edu

Preface

Risks in globally interconnected socio-environmental systems are complex: trade, migration, climate phenomena like El Niño, and other processes can both redistribute and modulate risks. We argue that risk must be investigated not only as a product of these systems but also as a force that rewires them through, for example, supply diversification, trade policy, insurance and other contracting, or cooperation. Two key questions arise: how do individuals and institutions perceive risks in these global, complex systems, and how do attempts to govern risks change how the systems function? We identify several areas for interdisciplinary research to address these questions.

Main

Governance of both non-renewable (e.g., oil, minerals) and renewable (e.g., fish, crops, forests) resources requires accounting for a range of risks. Risks, defined as the “potential for adverse consequences for human or ecological systems”[1], may arise from changes in market conditions (e.g., demand shocks, input shortages, trade policy changes), uncertainty about the current state of the resource (e.g., fish population size, soil quality, or remaining mineral reserves), or shifting environmental conditions (e.g., natural disasters or climate change), biological changes (e.g., disease or invasions). Risk and volatility in natural resource systems have direct impacts on human well-being[2], threaten access to credit if banks perceive repayment as uncertain, and dampen economic growth[3]. As a result, a range of actors, including those employed in the primary sector, but also traders, governments, conservation groups, and financial organizations, seek to understand these risks and reduce them. These efforts can backfire; physical suppression of variability and disturbance (e.g., wildfire suppression) can increase system susceptibility to larger shocks in the long run[4,5].

Modern risk assessment and governance are also challenged by growing interdependencies among distant coupled human-natural systems–a process known as telecoupling[6,7]. Teleconnections such as El Niño Southern Oscillation events, which have grown stronger in the past half century[8], are one source of telecoupling. Globalization has also dramatically increased trade, human migration, knowledge flows, and transmission of disease and invasive species[9]. As a result, some local resource decisions have distant environmental impacts (e.g., forest protection or reforestation efforts may shift deforestation elsewhere[10]) and the consequences of local environmental shocks are influenced by connections to other regions (e.g., remittances from migrants may help buffer economic consequences of natural disasters[11]). Taken together, these interdependencies complicate the task of risk assessment considerably. For example, access to export markets can provide a buffer against local demand shocks[12], but those same international trade links introduce new sources of risk. These new sources include supply booms in other locations driving down prices through competition; a pandemic like COVID-19 decimating demand in key destination markets; or trade propagating, lengthening, and intensifying financial crises as it did in 2008[13]. Threats to connectivity, e.g., through weaponization of trade[14], create a distinct type of structural risk.

Current approaches to studying risk in telecoupled systems are incomplete. Many studies of environmental risks ignore those that do not originate locally or use a highly simplified representation of interdependencies[15–19]. Recent efforts offer progress, characterizing[5,20] and providing examples of risks generated by complex socio-environmental systems, such as malaria risk induced by trade in deforestation-associated commodities[21] or snowpack-driven supply risk for imported agricultural products[22]. These analyses often take the connectivity of a telecoupled system as given and ask how it generates and redistributes risk. For example, tools from network science have traced the propagation of individual shocks in telecoupled systems[23,24] and highlighted how interdependencies may amplify risks well beyond those posed by individual system components ("systemic risk"[25]), even threatening system collapse[26]. However, the connectivity in telecoupled systems is not fixed – the ways in which people and institutions prepare for and seek to modify risks, including efforts to ensure "response diversity"[27], can change the network structure itself. Feedbacks from risk to the structure of telecoupled systems have been less explored and raise important questions about the system-level consequences of local risk governance and how individuals and institutions assess and govern risks in complex systems.

To this end, we argue that risk should be investigated not only as a product of telecoupled systems but also as a force that can rewire them in several different ways. Multinational risk pools that spread financial risks posed by natural disasters[28] offer one example. Those risk pools not only introduce new financial interdependencies among countries, they may also reduce incentives to physically manage risks via precautionary resource use or defensive expenditures (moral hazard), much as agricultural insurance could induce planting of riskier crops[29]. In turn, companies and countries that import from those disaster-prone areas could choose to diversify across import sources or even stop importing from risky areas, altering trade connectivity. Governments may also intervene if the resulting supply risks concern basic welfare of their citizens (e.g., food security), imposing export bans or subsidizing imports. Because all of these actions alter the connectivity of telecoupled systems, even answers to research and policy questions that are not explicitly about risk may still depend upon how risk is governed.

Types and examples of system rewiring

Attempts to govern risk often alter the existence and strength of links between parts of a telecoupled system (Fig. 1). Links can be strengthened or added, including by introducing new entities, such as financial institutions, conservation organizations, or international governing bodies (Fig. 1a, orange triangles). Similarly, links may be weakened or removed, such as through restriction or cessation of trade. These changes can occur alongside other, locally focused risk management efforts that do not alter connectivity, such as precautionary harvest, spatial closures, or conservation reserve programs.

To make these ideas concrete, we highlight three common sources of new connectivity that arise from risk governance (Fig. 1b-d). New public policies, partnerships, and treaties that directly target risk offer a clear starting point. For example, the Convention on International Trade in Endangered Species created new rules and reporting obligations to reduce species extinction risk, thereby linking parties to that agreement (Fig 1b), altering trade flows among them, and possibly creating new illicit trade flows elsewhere. Relatedly, conservation organizations seeking to limit risk of habitat or species loss may induce links between their project locations, as budget constraints may imply that spending to reduce risks in one place comes at the expense of spending and increased risk elsewhere. Beyond conservation, institutions created to govern wildfire risk may cover large regions (e.g., at the federal level), with both meetings and movement of firefighting crews introducing flows of knowledge across fire-exposed locations[30]. Even risk-related policies that do not explicitly seek to establish new connections may still do so: a city government building levees to manage flood risk could induce higher rates of human in-migration.

A second class of connectivity-altering risk governance tools are financial arrangements, with food systems offering several examples. Food importers concerned about supply risk may pursue complex strategies, such as purchasing land in other countries to exert control over production practices. Spatial patterns of foreign land ownership contracts (Fig. 1c) suggest these contracts affect the distribution of risks between the Northern and Southern Hemispheres. Futures and forward contracts for harvests play a similar role in redistributing price risk, with buyers–who may be in other countries–assuming those risks. Finally, crop insurance transfers production, price, or revenue risk from farmers to insurers located elsewhere in exchange for premiums. Insurers may pass along a portion of that risk through reinsurance contracts. Because many private insurers and reinsurers–including those who serve smallholder farmers–operate internationally, risks in one country could affect premiums or the availability of coverage in another (subject to regulation). Thus, the formation of some links to govern risk may prevent or constrain the formation of others. Similarly, because of limitations on which crops are insurable, insurance-based risk reduction strategies may constrain the countries in which different crops are grown, shaping market-based links between growing regions.

A third familiar way in which risk governance can alter the connectivity of telecoupled systems is through trade. Importers may diversify across source countries, adding links to limit price risk[31] or perceived risk of supply shortfalls; the same is true for exporters facing demand risk. The resulting network of trade flows– such as that for wheat in 2021 (Fig. 1d) – can be both dense and dynamic. The devastating heat wave and drought that hit Russia in 2010, together with price speculation and an export ban that ensued, provides one example. Russian wheat exports fell by 30% from 2009-2010 and remained lower than 2009 levels until 2014. Egypt, which had been heavily dependent on Russian wheat imports prior to the heat wave, continued to source from a diverse set of countries even after Russian wheat exports had rebounded in 2014 (Fig. 2) – a strategy consistent with risk governance. However, as time passed after the shock of 2010, Egypt's import shares of Russian wheat crept back up. This re-concentration mirrors the dynamics of risk governance after local disasters (e.g., floods), in which insurance uptake spikes after an event but fades with time[32]. More recently, perceived cereals supply risk in the face of the Russia-Ukraine war has re-ignited Egypt's efforts to diversify its wheat imports.

Not all risk governance approaches create new links in telecoupled systems; firms or governments may also weaken, break, or choose not to establish links deemed risky. Agri-food businesses dependent on international supply chains face not only production risk from suppliers, but also potentially reputational risk if food safety or poor working conditions in source regions come to light[33]. Those companies may choose to eliminate links deemed to pose reputational risks, decoupling some previously connected locations. Aware of price risks, governments often impose export restrictions to protect domestic consumers from escalating prices, especially for staple foods, temporarily breaking export links. Both the 2007-2008 food crisis and current Russia-Ukraine war offer recent high-profile examples. The resulting uncertainty over trade policy can reduce incentives for firms to invest in establishing trade links and infrastructure[34], limiting coupling well before any export bans take place.

Some risk governance approaches may both add new links and eliminate others. At the local level, communities may pursue different livelihoods if the health of nearby natural resources are perceived to be at risk, augmenting or replacing a set of distant locations with which they are connected. For example, coastal fishing communities facing a risk of stock collapse or simply high catch volatility may diversify into ecotourism. Doing so may replace or augment the community's connections from a focus on seafood export (and import of fishing supplies) to an emphasis on locations with likely tourists. This change in connectivity opens the coastal community to new flows to and from the new locations, which may also include flows of risk (e.g., economic downturn leading to reduced tourism).

Regardless of how risk governance alters system connectivity, the changes may have unintended consequences. Most changes aim to introduce negative (counteracting) feedbacks into complex systems; e.g., insurance payments offset farm income losses from drought, and risk-motivated trade policy often weakens export responses to world prices. However, those same changes can also create positive feedbacks in other parts of the system, contributing to systemic risk. A well-known example in food systems is the 2007-2008 food price crisis. A range of causes, including rising oil prices, weather-induced shortfalls in wheat production, and surging biofuels demand contributed to increased prices and fears of a shortage of affordable food[35]. Several governments responded with trade policy changes (e.g., export bans on rice and wheat in major exporting countries) intended to secure domestic supply for their citizens. Speculators saw an arbitrage opportunity and jumped in. Collectively, those actions only exacerbated food price increases elsewhere, raising food security risks in many other regions. In short, both policy and market responses introduced positive (reinforcing) feedbacks that led to far greater impacts than individual sources of risk would have suggested.

Factors that shape rewiring

If attempts to govern risk *can* reshape telecoupled systems, a natural follow-up question is when and where those changes are likely to occur. The answer to that question depends upon how individuals and institutions perceive and respond to risks arising in telecoupled systems, as well as what constraints may prevent rewiring from occurring.

Challenges for risk perception

Determining risk exposure in telecoupled systems may be quite challenging, with multiple sources of risks, links between locations, and governance elsewhere altering those links. Moreover, how users perceive risks emerging from telecoupled systems is likely different from perceptions of risks that originate locally, necessitating updated frameworks. Here we outline some of those challenges, summarized in Figure 3: distant connections (Fig. 3, box 1), number and variety of risks (Fig. 3, box 2), and complexity (Fig. 3, box 3).

First, telecoupling is characterized by distant connections (Fig. 3, box 1). Communities must assess and respond to risks of a distant origin, and distance likely affects perceptions of and responses to risk severity[36,37]. Direct experience with a particular hazard increases its salience even if it is less threatening than other, distant hazards[38,39]. More abstract threats generally demand less cognitive and emotional attention and are more likely ignored. As a result, distant hazards may receive less attention and scrutiny. Salience aside, the lack of direct personal experience with distant natural resource systems may also alter perceptions of risk arising from them[40], leading risk perceptions to be inaccurate, imprecise, or imbued with uncertainty.

Perceiving distant risks in telecoupled systems raises additional challenges and questions. First, information on risks originating in other countries may not be readily available, could be provided in a different language, or may be communicated differently due to variation in practice across regions. Likewise, perceived trustworthiness of the source of information is an important factor shaping risk perception, and people tend to trust sources within an identity group or socio-cultural community more[41,42]. Such sources may not be available for distant risks.

Distance in telecoupled systems is also dynamic. As physical and policy-imposed trade costs have come down, the relevance of distant risks to local outcomes has increased. At the same time, increasing availability of information could improve both perception and statistical assessment of distant risks. It remains to be seen how dynamic individual perceptions of distant risks are, and whether or not they track the changing relevance of geographically distant sources of risk.

The lower salience, information barriers, and dynamics of distant risks may favor delegation of risk assessment to institutions, which can introduce biases. Government agencies and political leaders have some incentive to downplay risks to secure public approval, and agencies tasked with risk assessment may have a mandate to monitor familiar local rather than distant risks[43], both of which could lead to underestimation of risk. Further, individuals may filter externally produced risk assessments through political or other ideological lenses, as exemplified in the polarized perception of viral and vaccine risks in the United States[44].

Second, telecoupled systems contain a greater number and variety of risks than do local systems (Fig. 3, box 2). Because attentional resources are finite, when new sources of risk command our attention, cognitive resources allocated to other hazards are likely to decrease[45]. Because attention alters environmental risk perception[46], how resource users assess overall risk may depend on which of those risk sources they attend to. This raises questions of whether and how resource users will prioritize or even triage assessment of risks across parts of a telecoupled system. Even if all risks are eventually attended to, the order in which risks are assessed could matter, especially if fatigue from assessing risk in some parts of the system affects risk perception in later-assessed areas[47,48].

The socio-environmental nature of telecoupled systems also means resource users must cope with a variety of risk types, including economic, policy, abiotic, and biological. Individuals may not perceive those risks identically, even if the different hazards they pose and probabilities of occurrence are comparable. For example, some communities could be very in tune with abiotic and biological risks through experience managing their local resources but unsure how to assess risks of social origin (e.g., price or trade policy shocks), especially if the people involved live in another city or country. Conversely, other communities could devote more time and effort to assessing social risks because they may perceive clear channels for influencing those risks, such as petitions or protests. Understanding whether and how individuals differentially assess various types of risks in telecoupled systems could be important for predicting behavior, and thus the functioning of the broader systems.

Third, the complexity of telecoupled systems poses clear challenges for both the perception of risk and evaluation of the consequences of actions intended to reduce risk (Fig. 3, box 3). Even if an individual has extensive knowledge of uncertainties governing distant natural resource systems, she must translate that knowledge into risk that is relevant to her own decision making. For example, a lobster fisher in Mexico may understand the environmental and biological variability facing lobster communities in Australia and New Zealand, but she must assess what that variability implies for her own livelihood. In a dynamic system with many distributed decision makers, the consequences of distant risk for local outcomes are often difficult to assess. The same complexity challenges assessment of the consequences of local actions intended to reduce risk, as there could be feedback from other parts of the system (including other communities attempting to reduce their own risk). Experimental evidence suggests that, in the face of such complexity, people may focus narrowly on readily available information[49], compounding challenges posed by language barriers and distance described earlier.

Complexity also challenges risk perception through cross-system spillovers and transformation of risk. One example is the 1972 collapse of the Peruvian anchoveta fishery, which set off a chain of events[50]: resulting fishmeal and fish oil shortages in the US led some farmers there to shift from wheat to soybeans–which can substitute for fishmeal and fish oil in animal feed–ultimately contributing to a wheat shortage that year in other countries. A second, macroeconomic example is the impact of fracking in the US on the oil-dependent Nigerian economy. With the advent of fracking, the United States transitioned from a net importer of crude oil to a net exporter, contributing to rapid and large declines in global oil prices[51]. This shock reduced the availability of foreign currencies the Nigerian Central Bank relied on to maintain its fixed exchange rate regime, devalued the Nigerian Naira, and produced a recession in the country, which is highly dependent on imports[52]. Assessing the risk of either chain of events requires knowledge well beyond a single natural system or market, combining understanding of production risks (of climate or technological origin), substitution patterns, and even monetary policy.

Aside from the cognitive demands it imposes, complexity may also lead participants in telecoupled systems to perceive that they have little control over their own outcomes – a sentiment likely reinforced by the distal nature of some risks. Low perceived control may have multiple consequences for risk perception and response. Given that greater perceived control can bias risk assessment toward optimism[53], we might expect risk assessment in telecoupled systems to suffer less from optimism bias. Low perceived control at the individual level may also heighten calls for government intervention. However, in complex, telecoupled systems, local and federal governments may be able to exert only limited influence over the risks to which their constituents are exposed, through either local policy or incomplete control over international agreements. Still, if governments do not intervene to limit constituent risks, political representatives could risk being unseated.

The complexity of telecoupled systems may give rise to systemic risks; however, it is unclear whether and how various system participants perceive them. Systemic risks are partly a function of how other people and institutions govern risk – how diversified they are, whether governments are likely to intervene if shocks do occur, and which of the many other tools discussed above will be deployed. How do individuals form beliefs about the potential risk governance behavior of others, especially when those others may be halfway across the globe? Moreover, because people update both their perception of and attitudes toward future risks having experienced a shock[54,55], maintaining updated beliefs about how others will govern risk in a telecoupled system seems especially daunting. While this sort of higher-order belief formation has long been recognized as central to the functioning of economies, understanding how individuals form and use those beliefs is an active area of research[56].

Constraints affecting risk governance

Understanding when and how risk governance will rewire telecoupled systems also requires acknowledging inequalities in access to relevant tools and resources. For example, the spatial autocorrelation of many environmental processes exposes nearby, low-cost trading partners to similar risks[57], making risk reduction via trade diversification more difficult or expensive for some vulnerable communities. Export-dependent communities may also contractually bear a disproportionate share of risks due to existing power dynamics with buyers in wealthier countries, raising environmental justice concerns. As for local risk reduction tools, some small banks or insurers may be unwilling to assume the risks that telecoupled systems pose for two reasons. First, accurately pricing complex risks arising in globally interconnected systems is difficult[58], and small financial institutions may not have the expertise or resources to do so. Second, risks across local resource users may be highly correlated due to shared environmental conditions or common export markets. A local bank or insurer may not wish to take on the risk of paying out to most local resource users at once, while larger, more diversified financial institutions in other locations may be more willing. Separately, risk preferences[59], access to risk-smoothing financial services[60], and participation in natural resource sectors such as agriculture[61] all vary with gender. As such, attempts to model adoption of different risk reduction strategies within telecoupled systems should allow for various forms of heterogeneity.

Disparities in access to information are also likely to magnify the risk perception challenges described earlier. Without direct experience or information, individuals may rely on observed behavior of peers to guide risk perceptions or subsequent actions[62,63]. This phenomenon is also quite common in interconnected financial markets: the high fixed costs of gathering country-specific information price out some banks or multinational investors[64]. As such, some investors mimic the decisions of others without accounting for the differences in characteristics that may make a particular action optimal for one firm but detrimental to another. In a natural resource setting, such "herding" behavior[65] could lead to convergence on risk governance choices that are not appropriate for some or all resource users. Thus, individuals or communities with access to information (or the resources to acquire it) may shape the risk-related behavior of those without it, entrenching existing inequities.

Paths forward

Improving our understanding of how risks rewire telecoupled systems should begin with a foundational understanding of the constraints and risk perception challenges just described. We highlight three sets of tools that could be useful. First, lab or field experiments can shed light on risk perception in telecoupled systems. One experimental design could investigate how the type or number of risks alters risk perception (Fig. 3, box 2) by presenting farmers with a fixed trade network, varying the number and type of risks within the network (e.g., potential drought or crop disease outbreaks in competing regions, or trade bans), and asking participants to explicitly assess risks. Probabilities and magnitudes of these events could be constructed in a way that they imply equivalent financial consequences for the participant, thereby isolating the role of type or number of risks for a fixed trade network. A second example experiment could investigate the role of system complexity (Fig. 3, box 3) on risk perception by placing a single risk (e.g., wildfire) in a trade network and asking participants (e.g. importers) to assess the probability of local impacts. Varying the network structure while keeping the probabilities of loss the same could allow for isolation of the role of system complexity in risk perception, building on studies of belief formation in network settings[66].

Second, comparative case studies could offer a complementary perspective, moving beyond network representations of telecoupled systems. One line of inquiry could examine institutional and policy factors that affect perception of and adaptation to telecoupled risks in organizations. Recent work on local risks[67] suggests that institutional adherence to historical processes, strategies, and (potentially idiosyncratic) definitions of success shape the adoption of specific risk reduction actions (echoing observations in ref. [43]). A similar comparative case study approach could assess whether these observations extend to a telecoupled context, e.g., how do different lobster fishing cooperatives in Mexico gather information on and adjust their export strategies in response to perceived demand risks in China? Do they fall back on readily available information as lab experiments[49] suggest, or, given the stakes for livelihoods, do cooperatives seek out unfamiliar sources, such as scientific reports or news stories in other languages? Beyond information gathering, do these organizations try new risk governance strategies or lean harder on historical precedent when the novelty and distal nature of risks in telecoupled systems means there is less *direct* experience on which to draw (Figure 3, box 1)? Comparative case studies in this and other empirical settings could begin to elucidate answers to these questions.

Third, observational statistical analyses could evaluate the insights generated by the first two approaches, identifying when and where connectivity-altering risk governance strategies are used in practice (e.g., When do possible crop losses trigger export bans?). These analyses would face at least two key identification challenges. First, changes in perceived risk may co-occur with and be influenced by actual shocks (e.g., a recent flood), so that separating effects of risk and effects of shocks is difficult. One option is to consider only connectivity changes that occur after announcement of a risk (e.g., public forecasts) but before a shock is realized. Another possibility is to use event studies to examine how shocks alter risk perceptions and responses in communities that are not directly affected. This was done for communities near nuclear power plants in China after the Fukushima disaster[68], though without our proposed focus on connectivity-altering responses to risk. A second key challenge is the statistical interference or spillovers inherent in telecoupled systems. Changes in risk will rarely affect a single location in isolation, and connectivity-altering risk governance will change where spillovers occur. Recent methodological advances, e.g., using network lags as instrumental variables[69], could offer more credible ways to draw causal inferences in this context.

Insights from these three and other approaches can guide development of models of telecoupled systems with risk-aware participants and risk-responsive connectivity. At a minimum, we should demand that these models offer improved predictive performance (e.g., for existence, magnitude, and volatility of system flows) in data-rich systems where it can be assessed. General equilibrium models provide one potential model framework; recent precedent in agricultural trade offers a tractable example incorporating trade, volatility, and risk preferences[70]. However, important questions remain on how often such systems are in equilibrium. Perceptions of risks and even risk preferences may take time to catch up with system dynamics or changing connectivity, or perceptions of risks may ebb and flow as in the example of Egypt's wheat import strategies. These behavioral dynamics are typically absent from general equilibrium models.

Agent-based models present an alternative modeling route: the rule-based behavior of agents (whether farmers, exporters, or policymakers) offers a clear place to incorporate risk-related behavior. Recent agent-based efforts to model global economic activity[71] and telecoupled agricultural systems[72] offer two promising starting points, but neither includes rules for how agents gather information about distant risks, how that information is used to form perceptions of risk, or how those perceptions alter rules governing action. Given the inherent flexibility of agent-based modeling, an important challenge will be extracting insights that generalize across a range of telecoupled systems[73].

Approaches from network science could help assess these generalizability concerns. Telecoupled systems have been usefully represented as networks[24,74], including in studies of how those networks change in response to shocks[75]—but not in response to risks. One idea is to model many telecoupled systems as multilayer networks with differing initial connectivity (e.g., trade and land ownership networks), then to ask which features of initial connectivity (e.g., edge density, degree distribution, clustering coefficients) predict higher levels of risk-induced rewiring, and which confer stability. Any relationships that do emerge could aid in characterizing when and where modeling insights apply. While relating initial network properties to network dynamics is not new, doing so for multilayer networks with endogenous link formation as in telecoupled systems makes identifying such relationships both interesting and challenging. A related idea is to instead vary a modeling assumption about risk-related behavior (e.g., risk aversion toward risks originating in another country) to observe how behavioral assumptions shape the telecoupled system network structure after any responses to risk. Inverting that relationship could potentially allow for inferring aspects of risk-related behavior from how the telecoupled system network structure evolved.

In sum, we advocate for the joint pursuit of micro-scale research on behavioral responses to risk and advances in macro-scale, risk-aware models of telecoupled systems. While ambitious, linking research across those scales is essential to determining who ultimately bears the risks that pervade telecoupled systems. If we erroneously assume connections in telecoupled systems are fixed or model their evolution based on an inaccurate understanding of behavioral responses to risk, our projections of which consumers are likely to be food insecure or which communities might see their livelihoods collapse are likely to be wrong. Over short time horizons, these errors could be minor, as communities may not have ample time to change their behavior or connectivity. However, many sustainability challenges entail risks and risk governance strategies that arise over much longer timescales.

This concern echoes the "Lucas critique" in economic forecasting[76], which casts doubt on predictions from phenomenological models that are not rooted in behavioral microfoundations. In our context, *historical* connectivity in telecoupled systems – trade networks, migration patterns, financial flows – offer only a phenomenological understanding of how telecoupled systems function. Our perspective boils down to a call to integrate modeling and behavioral science advances that allow analyses of telecoupled systems to overcome this critique, echoing related calls for integration of a range of human behaviors into social climate models[77]. Building risk-related behavior into increasingly complex models of telecoupled systems is only useful if the underlying behavioral foundations are plausible. To build out our knowledge of those foundations, we need to better understand the set of risks communities are exposed to in telecoupled systems, and how communities process and govern those risks. In short, we need an integrated investigation of how risks rewire telecoupled systems.

Contributions

S.J.M., L.E.D., and E.A.-B. identified the initial concept. M.T.H. conducted the initial literature review. S.J.M. led paper writing and revisions. L.E.D., M.T.H., U.J., A.R.C., K.A.B., and E.A.-B. contributed to writing and revision according to their areas of expertise.

Acknowledgements

S.J.M., L.E.D., and M.T.H. acknowledge support from the University of Colorado Research and Innovation Office. S.J.M. and U.J. acknowledge support from the United States National Science Foundation, Award #2314999.

Competing interests

The authors declare no competing interests.

References

1. Intergovernmental Panel on Climate Change (IPCC). *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2022). doi:10.1017/9781009157964.
2. Adger, W. N., Barnett, J., Heath, S. & Jarillo, S. Climate change affects multiple dimensions of well-being through impacts, information and policy responses. *Nat. Hum. Behav.* **6**, 1465–1473 (2022).
3. van der Ploeg, F. & Poelhekke, S. Volatility and the natural resource curse. *Oxf. Econ. Pap.* **61**, 727–760 (2009).

4. Holling, C. s. & Meffe, G. K. Command and Control and the Pathology of Natural Resource Management. *Conserv. Biol.* **10**, 328–337 (1996).
5. Nyström, M. *et al.* Anatomy and resilience of the global production ecosystem. *Nature* **575**, 98–108 (2019).
6. Liu, J. *et al.* Framing Sustainability in a Telecoupled World. *Ecol. Soc.* **18**, (2013).
7. Liu, J. Integration across a metacoupled world. *Ecol. Soc.* **22**, (2017).
8. Grothe, P. R. *et al.* Enhanced El Niño–Southern Oscillation Variability in Recent Decades. *Geophys. Res. Lett.* **47**, e2019GL083906 (2020).
9. Hulme, P. E. Trade, transport and trouble: managing invasive species pathways in an era of globalization. *J. Appl. Ecol.* **46**, 10–18 (2009).
10. Meyfroidt, P., Rudel, T. K. & Lambin, E. F. Forest transitions, trade, and the global displacement of land use. *Proc. Natl. Acad. Sci.* **107**, 20917–20922 (2010).
11. Pelling, M. & Uitto, J. I. Small island developing states: natural disaster vulnerability and global change. *Environ. Hazards* **3**, 49–62 (2001).
12. Almunia, M., Antràs, P., Lopez-Rodriguez, D. & Morales, E. Venting Out: Exports during a Domestic Slump. *Am. Econ. Rev.* **111**, 3611–3662 (2021).
13. Claessens, S., Tong, H. & Wei, S.-J. From the financial crisis to the real economy: Using firm-level data to identify transmission channels. *J. Int. Econ.* **88**, 375–387 (2012).
14. Farrell, H. & Newman, A. L. Weak links in finance and supply chains are easily weaponized. *Nature* **605**, 219–222 (2022).
15. Schweitzer, F. *et al.* Economic Networks: The New Challenges. *Science* **325**, 422–425 (2009).
16. Kasperski, S. & Holland, D. S. Income diversification and risk for fishermen. *Proc. Natl. Acad. Sci.* **110**, 2076–2081 (2013).
17. Deines, J. M., Liu, X. & Liu, J. Telecoupling in urban water systems: an examination of Beijing's imported water supply. *Water Int.* **41**, 251–270 (2016).

18. Hoekstra, A. Y. & Mekonnen, M. M. Imported water risk: the case of the UK. *Environ. Res. Lett.* **11**, 055002 (2016).
19. Simpson, N. P. *et al.* A framework for complex climate change risk assessment. *One Earth* **4**, 489–501 (2021).
20. Keys, P. W. *et al.* Anthropocene risk. *Nat. Sustain.* **2**, 667–673 (2019).
21. Chaves, L. S. M. *et al.* Global consumption and international trade in deforestation-associated commodities could influence malaria risk. *Nat. Commun.* **11**, 1258 (2020).
22. Qin, Y. *et al.* Snowmelt risk telecouplings for irrigated agriculture. *Nat. Clim. Change* **12**, 1007–1015 (2022).
23. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
24. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2021).
25. Centeno, M. A., Nag, M., Patterson, T. S., Shaver, A. & Windawi, A. J. The Emergence of Global Systemic Risk. *Annu. Rev. Sociol.* **41**, 65–85 (2015).
26. Helbing, D. Globally networked risks and how to respond. *Nature* **497**, 51–59 (2013).
27. Walker, B. *et al.* Response diversity as a sustainability strategy. *Nat. Sustain.* 1–9 (2023) doi:10.1038/s41893-022-01048-7.
28. Ciullo, A., Strobl, E., Meiler, S., Martius, O. & Bresch, D. N. Increasing countries' financial resilience through global catastrophe risk pooling. *Nat. Commun.* **14**, 922 (2023).
29. Cole, S., Giné, X. & Vickery, J. How Does Risk Management Influence Production Decisions? Evidence from a Field Experiment. *Rev. Financ. Stud.* **30**, 1935–1970 (2017).
30. Butsic, V., Kelly, M. & Moritz, M. A. Land Use and Wildfire: A Review of Local Interactions and Teleconnections. *Land* **4**, 140–156 (2015).
31. Muhammad, A. Source Diversification and Import Price Risk. *Am. J. Agric. Econ.* **94**, 801–814 (2012).

32. Atreya, A., Ferreira, S. & Michel-Kerjan, E. What drives households to buy flood insurance? New evidence from Georgia. *Ecol. Econ.* **117**, 153–161 (2015).
33. Rueda, X., Garrett, R. D. & Lambin, E. F. Corporate investments in supply chain sustainability: Selecting instruments in the agri-food industry. *J. Clean. Prod.* **142**, 2480–2492 (2017).
34. Handley, K. & Limão, N. Policy Uncertainty, Trade, and Welfare: Theory and Evidence for China and the United States. *Am. Econ. Rev.* **107**, 2731–2783 (2017).
35. Headey, D. & Fan, S. Anatomy of a crisis: the causes and consequences of surging food prices. *Agric. Econ.* **39**, 375–391 (2008).
36. Liberman, N. & Trope, Y. The Psychology of Transcending the Here and Now. *Science* **322**, 1201–1205 (2008).
37. Spence, A., Poortinga, W. & Pidgeon, N. The Psychological Distance of Climate Change. *Risk Anal.* **32**, 957–972 (2012).
38. Akerlof, K., Maibach, E. W., Fitzgerald, D., Cedeno, A. Y. & Neuman, A. Do people "personally experience" global warming, and if so how, and does it matter? *Glob. Environ. Change* **23**, 81–91 (2013).
39. McDonald, R. I., Chai, H. Y. & Newell, B. R. Personal experience and the 'psychological distance' of climate change: An integrative review. *J. Environ. Psychol.* **44**, 109–118 (2015).
40. Demski, C., Capstick, S., Pidgeon, N., Sposato, R. G. & Spence, A. Experience of extreme weather affects climate change mitigation and adaptation responses. *Clim. Change* **140**, 149–164 (2017).
41. Earle, T. C. Trust in Risk Management: A Model-Based Review of Empirical Research. *Risk Anal.* **30**, 541–574 (2010).
42. Siegrist, M. Trust and Risk Perception: A Critical Review of the Literature. *Risk Anal.* **41**, 480–490 (2021).

43. Boin, A., ‘t Hart, P., Stern, E. & Sundelius, B. *The Politics of Crisis Management: Public Leadership under Pressure*. (Cambridge University Press, 2016). doi:10.1017/9781316339756.
44. Fridman, A., Gershon, R. & Gneezy, A. COVID-19 and vaccine hesitancy: A longitudinal study. *PLOS ONE* **16**, e0250123 (2021).
45. Sisco, M. R. *et al.* Examining evidence for the Finite Pool of Worry and Finite Pool of Attention hypotheses. *Glob. Environ. Change* **78**, 102622 (2023).
46. Mrkva, K., Cole, J. C. & Van Boven, L. Attention increases environmental risk perception. *J. Exp. Psychol. Gen.* **150**, 83–102 (2021).
47. Blaywais, R. & Rosenboim, M. The effect of cognitive load on economic decisions. *Manag. Decis. Econ.* **40**, 993–999 (2019).
48. Hinson, J. M., Jameson, T. L. & Whitney, P. Impulsive decision making and working memory. *J. Exp. Psychol. Learn. Mem. Cogn.* **29**, 298–306 (2003).
49. Enke, B. What You See Is All There Is*. *Q. J. Econ.* **135**, 1363–1398 (2020).
50. Carlson, A. K., Taylor, W. W., Liu, J. & Orlic, I. Peruvian anchoveta as a telecoupled fisheries system. *Ecol. Soc.* **23**, (2018).
51. Jarrett, U., Mohaddes, K. & Mohtadi, H. Oil price volatility, financial institutions and economic growth. *Energy Policy* **126**, 131–144 (2019).
52. Department of Banking and Finance, Rivers State University, Port Harcourt, Nigeria, Iwedi, M., Igbanibo Dumini, S., & Department of Banking and Finance, Rivers State University, Port Harcourt, Nigeria. Nigeria Economy and the Politics of Recession: A Critique. *J. Adv. Econ. Finance* **2**, (2017).
53. Klein, C. T. F. & Helweg-Larsen, M. Perceived Control and the Optimistic Bias: A Meta-Analytic Review. *Psychol. Health* **17**, 437–446 (2002).
54. Chuang, Y. & Schechter, L. Stability of experimental and survey measures of risk, time, and social preferences: A review and some new results. *J. Dev. Econ.* **117**, 151–170 (2015).

55. Shum, M. & Xin, Y. Time-Varying Risk Aversion? Evidence from Near-Miss Accidents. *Rev. Econ. Stat.* **104**, 1317–1328 (2022).

56. Coibion, O., Gorodnichenko, Y., Kumar, S. & Ryngaert, J. Do You Know that I Know that You Know…? Higher-Order Beliefs in Survey Data*. *Q. J. Econ.* **136**, 1387–1446 (2021).

57. Dingel, J. I., Meng, K. C. & Hsiang, S. M. Spatial Correlation, Trade, and Inequality: Evidence from the Global Climate. Working Paper at https://doi.org/10.3386/w25447 (2019).

58. Blommestein, H. J. Difficulties in the Pricing of Risks in a Fast-Moving Financial Landscape (A Methodological Perspective). *J. Financ. Transform.* **22**, 23–32 (2008).

59. Eckel, C. C. & Grossman, P. J. Chapter 113 Men, Women and Risk Aversion: Experimental Evidence. in *Handbook of Experimental Economics Results* (eds. Plott, C. R. & Smith, V. L.) vol. 1 1061–1073 (Elsevier, 2008).

60. Adegbite, O. O. & Machethe, C. L. Bridging the financial inclusion gender gap in smallholder agriculture in Nigeria: An untapped potential for sustainable development. *World Dev.* **127**, 104755 (2020).

61. FAO. *The status of women in agrifood systems*. (FAO, 2023). doi:10.4060/cc5343en.

62. Pidgeon, N., Kasperson, R. E. & Slovic, P. *The Social Amplification of Risk*. (Cambridge University Press, 2003).

63. Wolf, J., Adger, W. N., Lorenzoni, I., Abrahamson, V. & Raine, R. Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities. *Glob. Environ. Change* **20**, 44–52 (2010).

64. Calvo, G. A. & Mendoza, E. G. Rational contagion and the globalization of securities markets. *J. Int. Econ.* **51**, 79–113 (2000).

65. Lynham, J. Identifying Peer Effects Using Gold Rushers. *Land Econ.* **93**, 527–548 (2017).

66. Grimm, V. & Mengel, F. Experiments on Belief Formation in Networks. *J. Eur. Econ. Assoc.* **18**, 49–82 (2020).

67. Vitale, C. Understanding the shift toward a risk-based approach in flood risk management, a comparative case study of three Italian rivers. *Environ. Sci. Policy* **146**, 13–23 (2023).

68. Huang, L. *et al.* Effect of the Fukushima nuclear accident on the risk perception of residents near a nuclear power plant in China. *Proc. Natl. Acad. Sci.* **110**, 19742–19747 (2013).

69. Comola, M. & Prina, S. Treatment Effect Accounting for Network Changes. *Rev. Econ. Stat.* **103**, 597–604 (2021).

70. Allen, T. & Atkin, D. Volatility and the Gains From Trade. *Econometrica* **90**, 2053–2092 (2022).

71. Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. & Sapio, A. Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. *Ecol. Econ.* **150**, 315–339 (2018).

72. Dou, Y. *et al.* Land-Use Changes in Distant Places: Implementation of a Telecoupled Agent-Based Model. *J. Artif. Soc. Soc. Simul.* **23**, 11 (2020).

73. O'Sullivan, D. *et al.* Strategic directions for agent-based modeling: avoiding the YAAWN syndrome. *J. Land Use Sci.* **11**, 177–187 (2016).

74. Schaffer-Smith, D. *et al.* Network analysis as a tool for quantifying the dynamics of metacoupled systems: an example using global soybean trade. *Ecol. Soc.* **23**, (2018).

75. Carlson, A. K., Young, T., Centeno, M. A., Levin, S. A. & Rubenstein, D. I. Boat to bowl: resilience through network rewiring of a community-supported fishery amid the COVID-19 pandemic. *Environ. Res. Lett.* **16**, 034054 (2021).

76. Lucas, R. E. Econometric policy evaluation: A critique. *Carnegie-Rochester Conf. Ser. Public Policy* **1**, 19–46 (1976).

77. Beckage, B., Moore, F. C. & Lacasse, K. Incorporating human behaviour into Earth system modelling. *Nat. Hum. Behav.* **6**, 1493–1502 (2022).

Figures

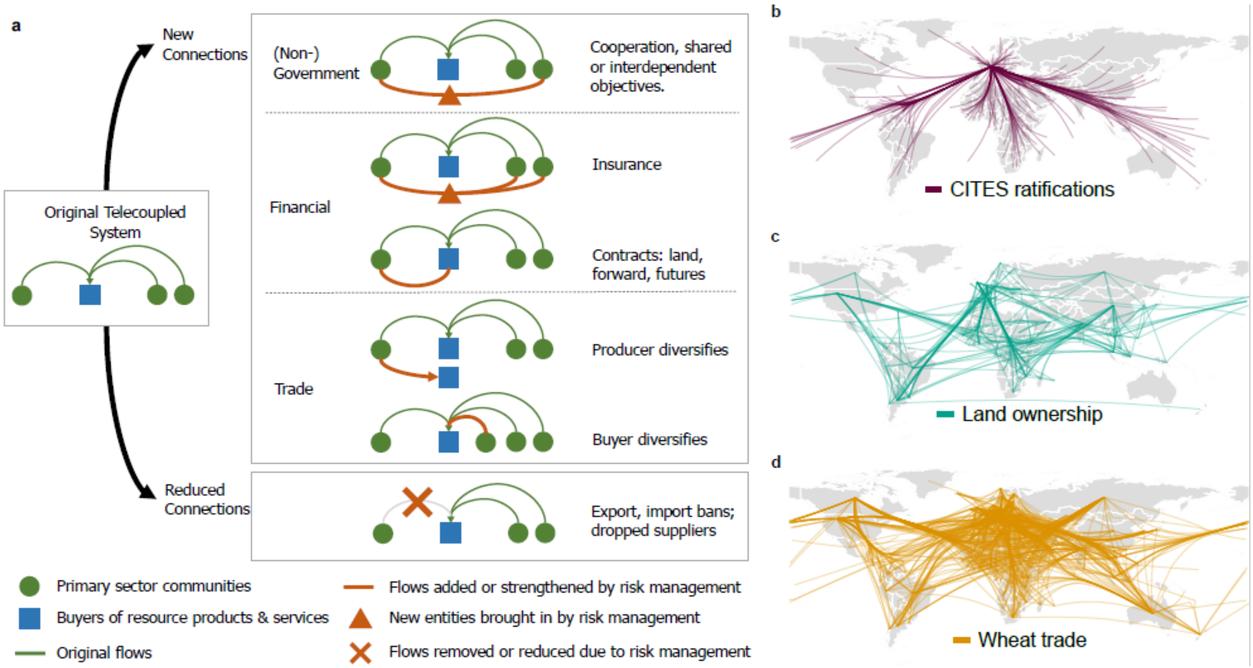

Fig. 1 | Risk governance can modify connectivity in telecoupled systems. a. Telecoupled systems link primary sector communities (green) and purchasers of resource-derived goods or services (blue), with complex risks arising from interconnected socio-environmental systems. Attempts to govern any one of those risks may include adding new links with other entities or locations ("New connections") or weakening or breaking links with distant systems ("Reduced connections"), possibly bringing in new institutions (orange triangles, e.g., insurers or international governance bodies) to help govern risk. These changes may alter the functioning of the telecoupled system overall, including changing the risks faced by other system participants across the globe. Examples of each type of increased connectivity are shown after modification by risk-related behavior in panels b-d: (b) Government or non-governmental organization: links from parties to the Convention on International Trade in Endangered Species to the Convention's depository in Switzerland (cites.org); (c) Financial: foreign land ownership contracts (landmatrix.org); (d) Trade: wheat export flows in 2021 (UN comtrade).

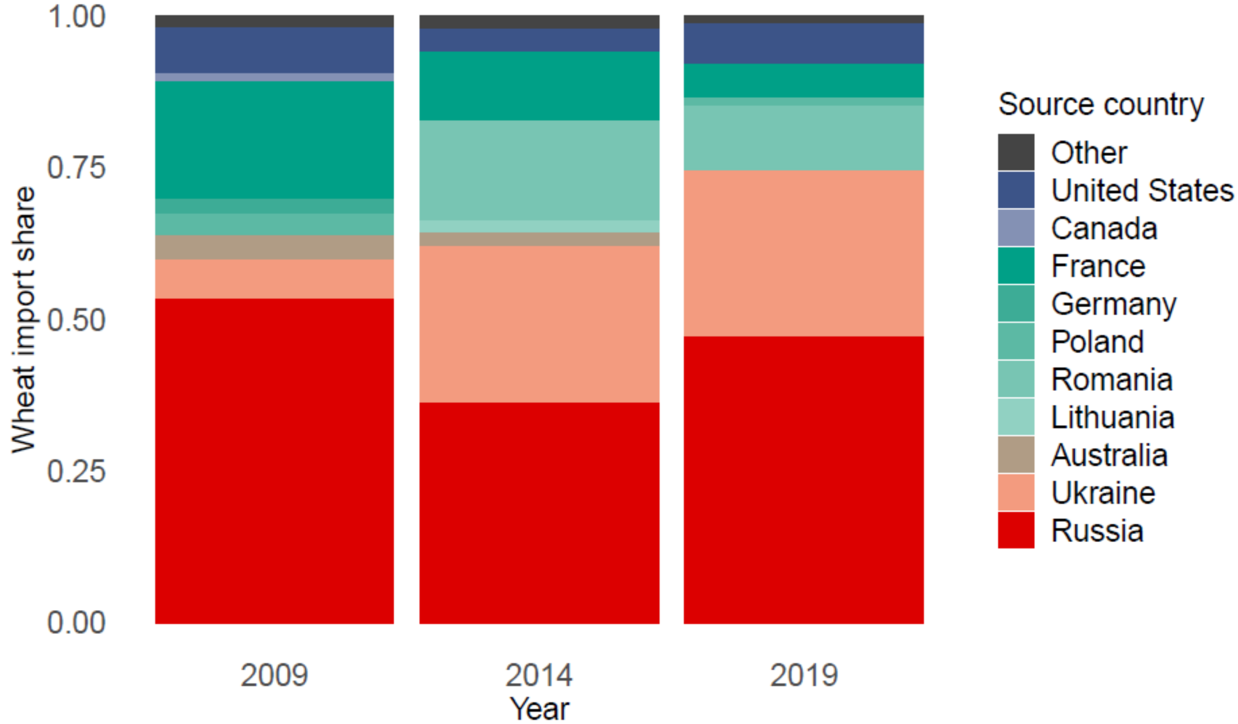

Fig. 2 | Diversification and re-concentration of wheat import shares in Egypt. Wheat imports in Egypt were primarily sourced from Russia in 2009. Following the 2010 heat wave in Russia, which decimated Russia's wheat supply, Egypt diversified their import sources by 2014. However, by 2019, Egypt's dependence on Russian wheat had returned. Import data are from UN Comtrade .(http://comtradeplus.un.org).

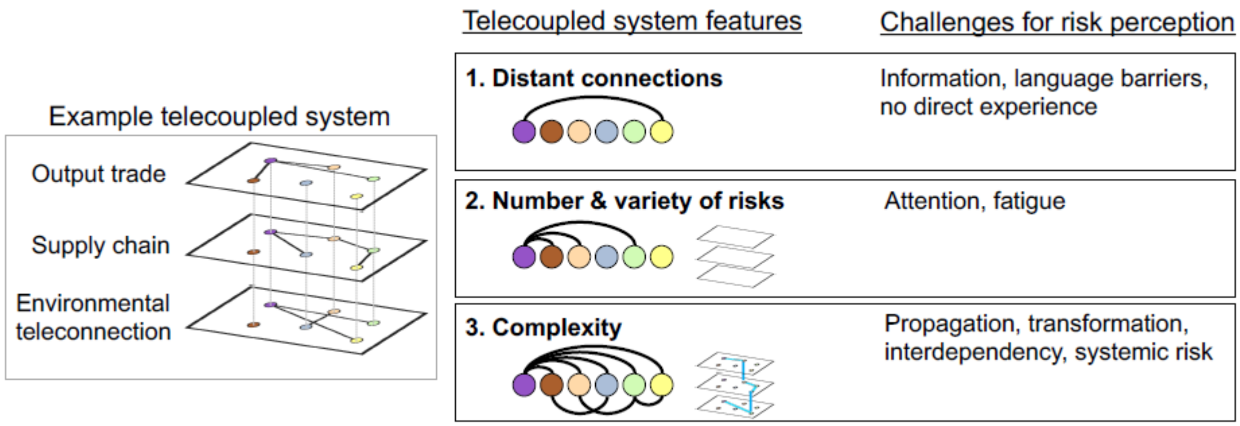

Fig. 3 | Challenges for risk perception in telecoupled systems. Communities (circles) are linked (lines) to others in several distinct ways (layers) in a simple hypothetical telecoupled system. The connectivity in telecoupled systems, together with the risk governance efforts of the various communities embedded in them, poses unique challenges for risk perception. Specifically, perceiving risks is made more difficult by the distance, number and types, and complexity of connections.