Response diversity as a sustainability strategy

Response Diversity as a Sustainability Strategy

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Preface

Financial advisors recommend a diverse portfolio to respond to market fluctuations across sectors. Similarly, nature has evolved a diverse portfolio of species to maintain ecosystem function to environmental fluctuations. In urban planning, public health, transport and communications, food production, and other domains however, this feature often seems ignored. As we enter an era of unprecedented turbulence at the planetary level, we argue that ample responses to this new reality – that is, response diversity – can no longer be taken for granted and must be actively designed and managed. We describe here just what response diversity is, how it is expressed, and how it can be enhanced and lost.

Introduction

In the morning of March 23, 2021, the giant container ship "Ever Given" was passing through the Suez Canal on its way to Rotterdam when it suddenly ran aground diagonally, blocking the entire canal. Because the ship was one of the largest in the world, traffic was jammed in both directions for six days. Hundreds of vessels came to a standstill, and billions of USD worth of trade were lost given the lack of alternative routes and modes of transport. Disruptions at bottlenecks like this (Figure 1) can have major consequences for billions of people, enterprises, and nations, influencing food supplies, prices, or access to spare parts, with potentially far-reaching social consequences[1].

Good preparation to avoid and respond to disruption requires access to a broad set of options to face unanticipated disruptions[2]. The current paradigms of lean sourcing, just-in-time and optimization ('efficiency') paradigms are ill-suited in this regard as they are not designed to handle unexpected new situations, such as the Ever Given incident[3] and the COVID pandemic, particularly occurring in tandem. Of course, widening the Suez Canal would increase the resilience of its traffic flow to incidents like the Ever Given but would be ineffective against other kinds of disruptions (e.g., political, armed conflicts) that might interrupt traffic – or if the size of ships continues to grow. Alternative responses include increasing storage capacity at receiving ends of the traffic, or diversifying how goods are transported (China's silk railroad, for example). This example highlights that, typically, a wide range of potential options are available for escaping rigid, vulnerable and therefore unsustainable structures[4,5].

[FIGURE 1[6–8]]

The Ever Given incident is symptomatic of a global trend where people, cultures and economies are increasingly linked across geographical locations and socioeconomic contexts[9,10], but with limited pathways for changing the links[11,12]. While this connectivity provides opportunities for humanity in terms of collective action to deal with global challenges (e.g., climate, pandemics, conflicts) and sharing ideas, goods and information[13], our capacity to understand and control global socioeconomic networks (e.g., trade,

finance) is becoming progressively more limited as complexity and interdependencies increase[14]. Further, humans have become a dominant global force with profound impacts on the Earth's biosphere[12,15–17]. The world is witnessing an increasing frequency, magnitude and duration of extreme events – including pandemics, heatwaves, mega-fires, droughts, floods, and storms[18]. The associated costs are significant in terms of economic and ecological disruption, reduced health, civil unrest, increased risk of geopolitical conflicts, human migration, and ultimately, human lives[19].

Increasing awareness of the many uncertainties humanity faces has led to calls for building resilience[20]– most notably greater resilience to threats in general rather than to particular threats. Of the aspects of such general resilience[21,22] the most crucial is having a diversity of responses to different kinds of disruptions. Though the value of diversification has long been recognised ("don't put all your eggs in one basket" – Cervantes 1612[23]), the rapid increase in frequency and severity of ecological, social and economic disruptions underlines its growing importance[18,24,25].

In this paper, we suggest that, if we wish to build general resilience to disruptions that cannot be exactly determined in advance, society needs to strengthen its *response diversity*. Response diversity is a system's variety of responses to disruptions, of all kinds. While this term originates from ecology[26], we argue it is critical to improving the resilience of any complex system. It suggests keeping options open for unexpected situations, which is consistent with theories about optimal decision-making under uncertainty and irreversibility[27–30].

As we work through the various facets of response diversity an important point to bear in mind is that, like resilience, it is a property of a system, and *per se* is neither "good" nor "bad". It can help maintain the current state of a system no matter whether it is deemed desirable or undesirable. If the state of a system and its trajectory are clearly undesirable the appropriate focus of response diversity should be on alternate transformational pathways. Because our reason for writing this paper is the serious loss of response diversity, the focus here is on when, where and how it is playing a positive role.

Despite the critical role response diversity plays in nature and in society at large, insights that extend beyond single sectors and disciplines are currently lacking. In this paper, we aim to fill this gap by integrating the different ways in which the concept is used and applied, highlighting the interconnectivity between different types of responses across sectors and scales. In particular, we explore just what response diversity means, how it is expressed in all kinds of systems, how it can be built and lost, its costs and benefits, and its implications for policy and governance. We conclude with some suggestions for strategies and policies to maintain or enhance response diversity. Importantly, our aim is not to scrutinise individual strategies for implementing response diversity in particular sectors but rather to provide

general guidelines relevant across disciplines, which can be explored in more detail within different specific contexts.

Response diversity

Living systems, from individual organisms to the global system, depend on having a set of processes (e.g. in ecosystems, photosynthesis, decomposition, predation; or in an economy, production and exchange of goods and services, waste management, transport) that enable that system to function. To ensure that these processes can persist in the long-term, requires that agents in a system (e.g. actors or organisms) have multiple ways by which they can respond to changes and disruptions. In other words, response diversity provides the raw material for adaptive behaviour (Figure 2*)*.

[FIGURE 2]

In ecosystems, there are different species that perform the same process but differ in the ways they respond to a particular disturbance[26]. Socioeconomic systems have also developed a variety of ways for providing essential services with different coping capacities, such as different types of water storage and delivery infrastructure, different modes of transportation, or different sources of various materials and products. Many small-scale irrigation systems have flexible institutions to manage environmental change, for example by altering water allocation as water availability changes[31]. Such adaptive institutions provide a diverse repertoire of 'software solutions' for social organization and thus maintain critical response diversity. Some of these strategies emerged after existing services had failed to respond to some new kind of shock; others were planned in advance. These diverse ways in which actors respond to a variety of shocks enables the function concerned to continue, thereby helping the system as a whole to continue functioning in much the same way. This is how response diversity confers resilience[26]. However, responding in different ways is also likely to have consequences beyond a particular function or scale, as we will illustrate.

We argue here that we need to identify different sources of response diversity, assess trends in those sources, and understand the implications of responding differently. In many systems response diversity is largely organizational, perhaps hierarchical as discussed in Levin et. al, 2022[32]. In this paper, in order to help unpack response diversity further and make it more operational, in addition to population and community responses (natural and human) we complement Levin et al. 2022[32] by focusing on spatial and temporal dimensions of response diversity.

Spatial responses In ecosystems, species operate at different spatial scales to avoid competition. This results in enhanced robustness over a wider range of environmental

conditions[33]. In coral reefs, for example, small territorial fish and sea urchins keep algal proliferation under control. So do schools of larger fish species that move over much wider areas. If a local storm hits the reef and kills less mobile species, species that operate at larger scales act as an important component of response diversity. They can continue to regulate algal populations and 'smooth' them in time[12,34]. In a similar way, migratory birds vary the locations and size of their territories as a way to increase their resilience to lack of food or difficult weather conditions.

In social systems, international trade provides spatial response diversity for buffering against disruptions at a national or local scale by providing alternative food sources, alternate distribution lines, or emergency supplies[35]. Trade from multiple sources, using various transport routes or modes, contributes to response diversity in the sense that if shocks to the availability of one exporter or importer occurs, trade can continue with another. A recent example is the vulnerability to potential energy shortages that several European countries are currently facing with the Russian invasion of Ukraine. In cities with limited open space, strong planning traditions and highly formalized procedures, peri-urban areas can contribute with both alternative spaces for different activities and less set planning and decision-making processes. Placed between the urban and rural governance systems, such areas often have developed ways for circumventing legal barriers or entrenched urban governance that have adverse effects at the scale of the peri-urban system[36]. Peri-urban areas may thus offer both alternative spaces and seedling alternative governance pathways, which may be explored in times of need. The adjacency to urban areas makes it a potential vital contribution to cities' capacity to respond to different perturbations.

Whether ecological or socioeconomic, spatial responses share a common feature: they integrate over space to smooth variation. These responses thus require mobility infrastructures that allow agents to move to resources or move the resources to them.

Temporal responses We define a temporal response as a shift in *when* and *how often* something is done, or in the amount of *time invested* in some activity. Such variation in resource use/extraction over time can be a necessary part of resilience, for example to compensate for variation in the amount of resources available to be extracted in different periods, thereby avoiding periods of great shortages and smoothing the flow/supply of valued resources. Common examples in human societies include storage in granaries and reservoirs, as well as banks. Many animals use similar strategies and store some of their food to be able to consume it later. For example, the Eurasian Jay (*Garrulus glandarius)* gathers oak (*Quercus* spp.) seeds that it buries in the soil for future consumption.

Insurance systems work in a similar way but add a scale dimension because present insurance payments from people currently not harmed can be used to compensate those

who are harmed. In the future the payment flows may go in other directions depending on who is harmed at the time. Importantly, insurance and financial systems work on trust: they are storages of commitments and require shared infrastructure (see collective responses below).

Like spatial responses, temporal responses all have a common feature: they integrate over time to smooth variation. These responses require storage infrastructure to accumulate and release resources at different times, that is, to 'move' them in time.

Cross-scale interactions in responses to disruptions While the dimensions of space and time are critical for response diversity, possible cross-scale interactions add a layer of complexity. For example, before the financial crisis in 2007-2008, individual banks used diversification to cope with uncertainty (i.e. increasing their response diversity). However, since many banks deployed similar risk management models, homogeneity of responses emerged at the global scale such that response diversity was eroded within the sector as a whole[37,38]. In other words, building response diversity at smaller scales can erode response diversity at larger scales if local initiatives copy each other[12,39] (Figure 3*)*. Examples of food systems and global supply chains illustrate this point (Box 1 and 2).

[FIGURE 3, BOX 1[12,40–42], BOX 2[1,12,35,43]]

Challenges associated with response diversity

Numerical metrics have limited utility for *measuring* response diversity. As this paper makes clear, response diversity emerges from a complex of attributes and modes of operating and any one of them may be limiting for any particular system when subjected to particular disturbances. Yet, there are approaches, frameworks and metrics that could help unpack this complexity. For example, one way to estimate response diversity in ecological systems is through functional metrics that allows us to measure the importance and distribution of response traits – that is, functional characteristics that determine an organism's response to perturbations – in a multi-dimensional functional trait space[44].

In social(-ecological) systems this could be translated into diversity of livelihood, management, and governance strategies that can be mobilized to cope with change[45]. However, it is important to note that strategies that provide response diversity for one type of disturbance may do nothing for another type of disturbance. For example, diversification of livelihood (e.g. selling and repairing of fishing gear, or using alternative trade networks) in small-scale fisheries to cope with impacts of variable fish stocks or overfishing, may have little effect if these alternative livelihoods are still relying on

abundant fish stocks and a disturbance affect the basic resource itself (i.e. “false” response diversity).

Subsequently, for each of the response diversity attributes and ways of operating we should ask which aspects of diversity are most critical for the system’s ability to respond to disturbances, and if so, in what ways could it be increased.

There are two overall challenges in *maintaining* response diversity: 1) managing trade-offs between using resources in the best way for present conditions versus using them to better deal with unexpected change tomorrow[46] and 2) managing trade-offs between investments targeted at coping with different classes of potential shocks. Resolving the first challenge requires balancing costly investments into maintaining or building diverse ways of responding to shocks. Assessing the benefits of various investments is very difficult due to the uncertainty in future conditions and equitably distributing the costs to present generations of managing variability raises difficult questions[47].

There are intertemporal trade-offs in the benefits and costs of response diversity, and because it is an emergent property of a complex system it is difficult to design in advance. In some circumstances a particular kind of disruption can be envisaged (as in the Suez Canal case) and appropriate alternative responses planned. In most cases investing in redundancy - back-up systems with some deliberate variation - and in modularity - to prevent uncontrolled spread of unwanted phenomena - can provide some degree of response diversity.

The second challenge to the fostering of response diversity has to do with the nature, frequency and intensity of disturbances, the scale at which they operate and interact, as well as the disconnect between social and ecological responses. Specifically, a fundamental feature of feedback systems capable of coping with shocks and variability is that ‘total fragility’ in a system is conserved, i.e. there is a minimum intrinsic level of fragility that cannot be eliminated. This basic principle from modern control theory limits our capacity to cope with all possible disturbances: investments in feedback system architectures (e.g. response diversity) focused, for example, on disturbances of a certain frequency range *necessarily* make the system vulnerable or ‘fragile’ to disturbances at other frequency ranges[48]. This notion has been extended to biological systems to demonstrate hard robustness limits in systems with ‘highly optimised tolerance’[49] and underpins general theories of biological robustness[50] wherein systems must trade-off optimality, robustness, and evolvability[51]. Other work has extended the basic principle of robustness-fragility trade-offs to social-ecological systems[52,53] and have illustrated, for example, trade-offs between increasing robustness to uncertainty in the economic domain at the cost of increasing vulnerability to uncertainty in the ecological domain. Such fundamental design considerations and the cost of response diversity and the necessary compromises in

addressing the question of 'resilience of what to what' must play a key role in strategies for strengthening response diversity.

To serve its purpose, response diversity must maintain the agents and structures that ensure system stability over time. Insurance systems, for instance, were described above as a temporal response to dealing with unexpected disruptions. They typically cover situations where the expected consequences of a shock are high and the probability of its occurrence is low and uncorrelated among insured individuals. The insured bear the cost of response diversity in the form of the insurance premium. Sometimes the cost can be too high even for insurance companies. In these situations, the reinsurance industry can help spread the risks over many insurance companies, in different parts of the world subject to different kinds of shocks, and in this way develop response diversity. This enables the insurance companies and their insured bodies to remain resilient to the range of shocks they can expect.

Nevertheless, situations where the probability of shocks or bad outcomes are strongly correlated at the global scale are harder to deal with through insurance and reinsurance systems, which often include force majeure clauses against them. Climate change dynamics, for example, are likely to trigger correlated shocks in large regions. Insurance might assist the victims of droughts, large forest fires, or inundations even if these occur simultaneously (as witnessed in the summer of 2021 when central Europe suffered unusually large and severe inundations while wildfires across several continents were larger than in recorded history), as long as such events are sufficiently rare/low-cost; but less so if damage is overwhelmingly large or occurs simultaneously for almost everyone.

Climate change contributes to correlated hazard risks globally while also inducing synergy of multi-hazard risks. Reinsurance is important but falls short if risks are too strongly correlated globally[54]. Adaptation to risks by households and companies then becomes more relevant, and requires diversity in itself because the best strategies in local situations to safeguard against hazards are not always clear. As an example, for flooding hazards potential strategies include flood protection, reduction of the peak flows, mitigation of vulnerability, and relocation to safer areas[55].

Another challenge is the current disconnect between ecological and socio-economic responses. Insurance against weather-related crop failure, for example, provides an opportunity for farmers to cover themselves against crop losses caused by droughts. These insurances are not based on directly measured loss of crops, but payouts are instead triggered by an index, such as a predefined threshold in rainfall[56]. Farmers with access to this type of insurance seem more prone to invest in high profit but riskier crops[57]. Since these insurances are often also coupled to the adoption of commercial inputs, they may reinforce the simplification of agricultural landscapes and the homogenization of practices[12].

In general, support to maintain functions in risky environments provides incentives to continue with increasingly risky behaviour and associated loss of response diversity.

The world currently faces many serious problems - disease epidemics, climate change, economic meltdown, social turmoil, war, etc. – and as this has unfolded, we seem to have moved from a social-ecological system with high resilience in its biosphere part but little in the social part to one with much more resilience in its social part (for now) at the expense of its biosphere, as illustrated by the example above. The lack of appropriate institutions for dealing with these problems has been identified as a major cause of the inability to act[58]. The process has undoubtedly been exacerbated by humanity's overall success in increasing its short-term well-being to an unprecedented extent (e.g. the number of people and the amount of welfare they enjoy on average).

Attempting to increase resilience in the social system without acknowledging the need to maintain it in ecosystems has led to a general decrease in social-ecological response diversity[12]. Hence, understanding the combined social-ecological responses across scales is crucial when evaluating intentionally designed response diversity and redundancy.

Finally, justice and equity issues loom large in the challenges facing programs for response diversity. As we have described above, there are often direct or indirect costs to responding, and these can be shared more or less equally. As was clearly shown already by Elmqvist et al. 2003[26], maintaining high-level, aggregate functional performance is often a question of some responses being successful whilst others fail. Ecologically or evolutionary, this has no normative implications, but when expanding response diversity to people and social systems it can. Response diversity often includes options that are exploitative or long-term degenerative. The roving bandits syndrome[59], for example, illustrates a response option that is beneficial to powerful companies and their customers but disastrous for small-scale fishermen in the targeted regions. Less overt, any resources, financial or otherwise, invested in response diversity incur an opportunity cost because they could have been invested elsewhere to generate a future stream of benefits. Who bears that cost? Hence improvements in response diversity in some dimensions could compromise social response diversity by increasing inequalities and putting more pressure on some vulnerable groups of people, which may increase the risks of social unrest.

Strategies to enhance response diversity

To address the previous challenges to building and maintaining response diversity, we suggest that a critical first step is to create widespread awareness of the meaning of response diversity and its crucial role in responding to unexpected change and sustaining long run wellbeing. An appropriate second step would be a search for 'win-wins', where

response diversity is enhanced as a by-product of other well-being enhancing investments, accompanied by direct investments in response diversity, and we propose strategies to nurture it. While these may be quite straightforward, they require some societal awareness about the role of response diversity and accompanying collective action which may be more difficult to achieve. It is also important to notice that responding to multiple and compounded crises requires a combination of responses at both local and larger scales. Although many crises are local in nature, in a globalised and interconnected world, local communities are often deeply embedded within larger scale dynamics. Therefore, the fostering of strategies to enhance response diversity across multiple scales is crucial.

Strategy development Strategies for promoting response diversity logically build on the understanding of how it has evolved and been developed through temporal and spatial responses to the variability in natural and social environments, as described earlier. The strategies can be developed by individuals, organisations, and governments and in all cases a diverse portfolio can provide resilience by *substituting*, *complementing*, or *compensating* for other elements or variables.

In situations where *substitutable* options exist, each one is likely to perform best in different contexts or situations. The performance and outcomes of these alternative responses are largely independent of each other, though they may be used in parallel as adaptations to the inherent unpredictability of the future. Examples include investment options in a diversified investment portfolio and duplication of production facilities in different parts of a country or the world. Parts of this response diversity may be lost if some aspects irrelevant to profitability or quality can influence investment decisions. For example, some types of investments, e.g. in genetically modified organisms, may be boycotted for ethical reasons or some types of new technology may be at a disadvantage due to unintended restrictions from existing legislation. In ecological systems, an example of substitutable benefits in livestock production on rangelands[60] showed that some of the minor grass species are analogues of, and can substitute for, the dominant, more productive species in terms of the ecosystem functions they perform. They differ in terms of their capabilities to respond to environmental stresses and disturbances, such as droughts and high grazing pressure, and can replace the dominants that are reduced or eliminated by such disturbances.

Response options can be c*omplementary.* Each is partial and limited in scope, and the outcome of the response depends on other responses. They are adaptations to the multi-dimensional nature of solutions to most problems. A strategy for harnessing this diversity may require simultaneous action on multiple fronts and cognitive capacity or coordination that may not exist, especially under stress/crisis. Responding to climate change in farming, for example, will likely include agricultural production practices, financial hedging and other pricing strategies and political lobbying as complementary responses. Identifying

such complementary options generally requires a systemic approach where focus of investigations is on the whole picture rather than on specific details[61]. Such an approach combined with modelling of different options individually and in combination can help provide novel insights, for example about what combination of policy instruments could address as many planetary pressures as possible[62].

In *compensatory* responses, failure of, or the absence of, one kind of response may require changing the strategy being used, for example from using incentives (economic, ethical…) to interventions (policy, technology, ecological). At the scale of an individual organism, diversity to pathogens is reflected in the interplay between behavioural and physiological responses. Behaviours may reduce exposure to pathogens, for example social distancing can decrease exposure, or varied diets and lifestyle can make the body more resilient to pathogens in general. But when this fails, the immune system must take over. It prepares in advance - it is adaptive and learns from its past. Immune memory (information storage) is "the ability of antigen-specific cells of the immune system to recognize pathogens previously encountered and to produce a qualitatively and quantitatively different response (i.e., faster or more robust) than the first encounter"[63]. Additionally, the immune system has many redundancies in case one defense fails[64].

In complex systems like cities, developing strategies for building and then harnessing response diversity is a challenge. Urban adaptation to extreme weather events, for example, has traditionally been seen as a problem best addressed through engineered infrastructure solutions (levees against flooding or air conditioning against heat waves). However, with changing disturbance regimes and an acknowledgement of the need to address multiple issues, nature-based solutions and hybrid approaches have gained traction[65], combining different components and actors to offer alternative ways to implement and govern solutions.

Reducing flood risk in many cities, for instance, is shifting from reliance on highly engineered infrastructure to more integrated solutions with a diversity of designed living systems, such as reducing impervious surfaces and improving wetlands, building bioswales and green roofs[66]. This hybridity diversifies the ways in which cities can respond to increasing climate variability[67]. All of this is further complicated by the fact that different parts of a city may need different responses, depending on social capital and the effectiveness of governance, both of which can vary across a city.

Beyond particular options as outlined above, strategies for building response diversity must involve diversity in goals and/or capabilities. Human (individual and collective) responses to natural and anthropogenic disruptions are needed not only because of the inherent unpredictability of future conditions or to build in redundancy that can compensate for local failures, but also because people differ in their values, concerns, and

goals. Arguably such heterogeneity at the individual or cultural level evolved as a strategy to ensure response diversity of the population as a whole. Individualist vs. collectivist societies (and the individuals within them) construct their reality in qualitatively distinct ways and see different classes of risk as actionable[68]. They not only pursue alternative meta-goals to different degrees (e.g. personal utility vs. social welfare), but do so by relying differentially on qualitatively disparate decision processes (e.g. analytic, emotion-based, or rule-based), providing response diversity at the process level[69]. At the population/ group level, response diversity can also be expressed as heterogeneity in different agents' capabilities. People trained in analytical thinking and social planning assess and use available information differently from those who rely mostly on intuition, personal experience, and social networks. The two different approaches provide diverse and complementary assessments of societal risks and appropriate responses[70].

Traditional strategies to nurture diversity include, for example, compensating landowners for setting aside land and wetlands; planting crops to reduce soil erosion; encouraging local markets for locally-grown products; providing labelling for traditionally made products, among others. Transforming society toward sustainability, however, requires more: a change of vision, goals and values that can guide system design and provide enough agency to influence institutions and policies[4,71]. Such norm shifts can be achieved through appropriate and timely supporting policies[72] and this change must go beyond behavioural norms to deeper belief system elements. Hall and LaMont[73] for example, argue that we need to move beyond the culture of 'hard work' and consumption-based status that gives most of the rewards of the economic system to few. Ideally the question 'how do I lead a meaningful life?' should trigger a wide diversity of answers, not only variations of achieving status through a high consumption level.

Related to the need for norm shifts is a need to encourage variety in practices, rather than just the one "best" way of doing things. Applying top-down control systematically combined with similar types of objectives, like new public management, is likely to result in uniform solutions. These have proven to be often ill-adapted to disturbances like the Covid-19 pandemic. For example, many regions had rationalised away contingency stocks of medical supplies which were suddenly needed. Balancing top-down approaches with greater bottom-up inputs could promote a greater variety of practices and solutions to problems.

In practical terms, two complementary areas require particular policies. First, each sector of concern (e.g. health, economics, agriculture, industry) must ask and answer the question: "What are the likely/possible disruptions this sector might face, and what kinds of response diversity are needed to cope with them?". Second, they must ask the complementary question: "How do proposed changes aimed at increasing efficiency, savings, etc. also influence changes in response diversity, and what are the possible

consequences of these changes in the short and long term?" Proposed changes in development and operational procedures in governments, industries and corporations should include a formal obligation to explicitly answer these questions.

Given the trade-offs associated with nurturing response diversity, mainly in the form of foregone short-term efficiency, direct investment to nurture diversity in social and ecological systems will likely meet with push back from special interest groups. While direct public investment will provide diversity, it is also necessary to actively search for spillovers from private investments and actions and focus particularly on identifying those assets with positive spillovers, i.e., positive unintended consequences rather than negative ones. In that context it is important that public authorities maintain their role of gatekeepers and rule setters rather than trying to please particular industries of national economic importance. Putting in place and enforcing antitrust regulations is one way to ensure that diversity can be maintained.

Broad agreements are easy to reach, but real change requires working out the details of costs, benefits, winners and losers, and actually implementing agreements. Identifying and addressing the trade-offs related to response diversity requires the capacity to investigate consequences of actions in time and space. This will enable the chance to identify negative long-term trends and potential reinforcing feedback loops of concern as well as potentially correlated shocks. Hence planning capacity focusing on systemic approaches are crucial to that end and can help identify win-win situations, and shortcuts in an overly complex planning situation[61].

Finally, it might be helpful to identify principles that societies can agree on which may contribute to response diversity. Accordingly, in Table 1 we conclude with seven tentative principles to develop policies across ecological, social and economic domains, from local to global scales, for building and maintaining response diversity, and therefore resilience. We use the term "tools" in a specific sense: we define tools as a set of tailor-made responses to a particular situation.

[TABLE 1 here]

In order to further explore how these principles will translate in different contexts and how they could be implemented across local and regional policies we foresee that co-production of knowledge – that is, collaborative processes that convene academic and non-academic actors around problem framing and trust building, through knowledge generation[74] – can play an important role.

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Author contributions

B.W., A-S.C., M.N., J.M.A., E.A., T.E. and C.Q. led the conceptualization and writing of the paper. All authors contributed to conceptualization and editing. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

TABLES:

Table 1. Seven tentative principles to develop policies across ecological, social and economic domains

Recognize that risks can be reduced with a variety of tools in the toolbox.	Having different ways for responding to the same or different kinds of disruptions confers resilience. Apparently redundant elements/ processes can in fact be response diversity, enabling the system to perform the same function in different ways with different responses to different kinds of disruptions
Acknowledge the useful set of tools is context-dependent	Responses differ in terms of their spatial, temporal and functional scales, and include substitutable, complementary and compensatory options.
Account for the social benefits of having a toolbox with a variety of tools, which are otherwise ignored in private exchange	Economic efficiency - getting more for less through market exchange - can ignore social benefits of maintaining different tools. The cost of creating or maintaining response diversity leads to its erosion through efficiency drives, thereby increasing the potential costs of a lack of response diversity
Account for multiple scales when choosing which tools to use	There are trade-offs between response diversity at multiple scales in space and time. Examples: increasing different sources and kinds of supplies at a large scale can lead to a decline in the variety of local scale sources; if individual banks (local scale) use similar risk-management models, homogeneity in responses is cultivated within the sector as a whole (global scale).

Recognize that tools are interdependent	Different responses to different disruptions may intersect with/influence a reorganisation process in different phases and in different (complementary or contradictory) ways

Be flexible in which tool is best over time.	Optimising response strategies to the current pattern of disruption can be detrimental if the pattern of disruptions changes. Two examples: ignoring climate change; not considering multiple potential disruptions in supply chains
Account for how a tool can create moral hazard (unintended behavioural responses).	Support to maintain function in risky environments can lead to increasingly risky behaviour or unequal, disproportionate costs and loss of response diversity. A classic example is insurance in agriculture

FIGURE LEGENDS:

Figure 1. Major maritime choke points, and primary (solid blue) and secondary (dotted blue) shipping routes. Ocean shipping accounts for the bulk of all transportation in international trade (80% by volume and 70% of value)[6,7]. Numbers (%) are estimates of global grain (wheat, maize, rice, soy) volumes passing maritime choke points in 2020. Moderate (yellow, minimal delay for shipments), High (red, significant cost due to transit time and shipping costs), and Critical (purple, no obvious alternative maritime route is available). Many commodities pass several maritime choke points toward their final destination, and must also pass coastal (ports) and inland (railway, waterway, road networks) choke points. Volume estimates, examples of disruptions, and shipping routes are adapted from Chatham House Report 2017: Chokepoints and Vulnerabilities in Global Food Trade[8], and L. Wellesley (pers. com).

Figure 2. A conceptual illustration of response diversity. A high diverse system (top left) (e.g. agroecosystems) is more likely to maintain system functions and processes when facing a disturbance, whereas a low diverse system (low left) (e.g. mono-culture) is highly vulnerable to a specific disturbance. Symbols of different colours represent the diversity (n=) of agents/structures in a system (e.g. species, traits, reserves, strategies).

Figure 3. An illustration of how response diversity manifests at different spatial scales and how this can influence the propagation of risk. Circles with different colours represent the

diversity (n=) of agents/structures (e.g. species, traits, reserves, strategies) in a system at local and global (beta-) scales.

BOXES:

Box 1. *The effects of cross-scale interactions on response diversity in food systems*

The focus on efficient agricultural production at the global scale can undermine response diversity at local scales. Over the past 50 years, the portfolio of global food supply has become increasingly species-poor, and is now based on just a few key crops, mainly maize, wheat, rice and barley[40]. Moreover, local varieties of these crops are being lost, as a smaller number of high-yielding varieties are increasingly being used in highly controlled systems of industrialized agriculture.

In addition, perturbations that naturally select for particular species traits or practices in any given landscape have disappeared from modern agricultural production systems. As a result, the response diversity of agricultural landscapes is gradually eroding. Moreover, the widespread practice of "one-size-fits all" industrialized agriculture is associated with the homogenization of actors and scale increases in the global food system. This means that not only ecological response diversity, but also social response diversity is lost in agricultural landscapes around the world[12,41].

The widespread consumption of just a handful of globally marketed crops leaves food systems vulnerable to disturbances such as climate change, crop failures, volatility of food prices, or disruptions in trade – as most recently witnessed in the case of wheat shortages following Russia's attack on Ukraine. Instead of growing diverse portfolios of distinct, locally adapted crops, many countries in eastern Africa substantially depend on importing large quantities of wheat from Russia and Ukraine[42], causing a loss in local social-ecological response diversity with potentially far-reaching consequences for human well-being.

Box 2. *Response diversity in global supply chains*

The vulnerability of global supply chains was highlighted by a number of recent events: the Covid-19 pandemic, the grounding of the "Ever Given" ship in the Suez Canal, and disruptions in the supply of natural gas due to Russia's invasion of Ukraine. Albeit distinct in nature, these events exposed the dependence of our economies on few suppliers and optimized production-consumption-transport

schedules. This translated into negative impacts on the cost of living or even the livelihoods of people around the world.

International supply chains and trade play an important role in smoothing out variations in resource availability. But trends in organizational structure, markets and technologies towards increasing-returns-to scale, just-in-time inventories, increased interconnectedness and reduced modularity potentially reduce response diversity, thereby weakening resilience to extreme events[12,35].

For response diversity it does not matter whether products are local or foreign, as long as they come from a variety of independent origins. To illustrate, in 2017 Australia imported 5950 different products from 223 countries (which includes distinct regions within a sovereign nation). Although the majority came from five countries, only one in 20 imports were considered vulnerable[43]. Altogether, this suggests considerable response diversity – very much in contrast to, for example, the high dependence of several eastern and central European countries on Russian gas.

Given the changing nature of supply chains, a diversity of responses to possible disruptions is needed, at multiple scales: from the individual (substituting foods), through the company (switching sources), to the government level (holding strategic reserves)[1]. The combination of individual liberty and heterogeneity, transparent markets, antitrust regulation, and possibly sector support (e.g. of local agriculture and energy generation) may provide minimum conditions to guarantee response diversity of supply chains.

References

1. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2021).
2. Lempert, R. J. & Collins, M. T. Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches. *Risk Anal.* **27**, 1009–1026 (2007).
3. Garnett, P., Doherty, B. & Heron, T. Vulnerability of the United Kingdom's food supply chains exposed by COVID-19. *Nat. Food* **1**, 315–318 (2020).
4. Abson, D. J. *et al.* Leverage points for sustainability transformation. *Ambio* **46**, 30–39 (2017).

5. Westley, F. *et al.* Tipping Toward Sustainability: Emerging Pathways of Transformation. *AMBIO* **40**, 762–780 (2011).
6. United Nations Conference on Trade and Development. *Review of maritime transport 2017*. (2017).
7. UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT. *REVIEW OF MARITIME TRANSPORT 2018.* (UNITED NATIONS, 2019).
8. Wellesley, L., Preston, F., Lehne, J. & Bailey, R. Chokepoints in global food trade: Assessing the risk. *Res. Transp. Bus. Manag.* **25**, 15–28 (2017).
9. Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. *Anthr. Rev.* **2**, 81–98 (2015).
10. Jouffray, J.-B., Blasiak, R., Norström, A. V., Österblom, H. & Nyström, M. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. *One Earth* **2**, 43–54 (2020).
11. Adger, W. N., Eakin, H. & Winkels, A. Nested and teleconnected vulnerabilities to environmental change. *Front. Ecol. Environ.* **7**, 150–157 (2009).
12. Nyström, M. *et al.* Anatomy and resilience of the global production ecosystem. *Nature* **575**, 98–108 (2019).
13. Mason, W. & Watts, D. J. Collaborative learning in networks. *Proc. Natl. Acad. Sci.* **109**, 764–769 (2012).
14. Helbing, D. Globally networked risks and how to respond. *Nature* **497**, 51–59 (2013).
15. Worm, B. & Paine, R. T. Humans as a Hyperkeystone Species. *Trends Ecol. Evol.* **31**, 600–607 (2016).
16. Crutzen, P. J. & Stoermer, E. F. “The ‘Anthropocene’” (2000). in *The Future of Nature* (eds. Robin, L., Sörlin, S. & Warde, P.) 479–490 (Yale University Press, 2017). doi:10.12987/9780300188479-041.
17. Ellis, E. C. Anthropogenic transformation of the terrestrial biosphere. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **369**, 1010–1035 (2011).

18. Senevirante, S. I. *Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1513–1766 (2021).

19. Frank, A. B. *et al.* Dealing with femtorisks in international relations. *Proc. Natl. Acad. Sci.* **111**, 17356–17362 (2014).

20. Folke, C. *et al.* Our future in the Anthropocene biosphere. *Ambio* **50**, 834–869 (2021).

21. Walker, B. & Salt, D. *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function*. (Island Press/Center for Resource Economics, 2012). doi:10.5822/978-1-61091-231-0.

22. *Principles for Building Resilience: Sustaining Ecosystem Services in Social–Ecological Systems*. (Cambridge University Press, 2015). doi:10.1017/CBO9781316014240.

23. Cervantes Saavedra, M. de & Rutherford, J. *Don Quixote: the ingenious Hidalgo de la Mancha*. (Penguin, 2003).

24. Coronese, M., Lamperti, F., Keller, K., Chiaromonte, F. & Roventini, A. Evidence for sharp increase in the economic damages of extreme natural disasters. *Proc. Natl. Acad. Sci.* **116**, 21450–21455 (2019).

25. Cottrell, R. S. *et al.* Food production shocks across land and sea. *Nat. Sustain.* **2**, 130–137 (2019).

26. Elmqvist, T. *et al.* Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* **1**, 488–494 (2003).

27. Arrow, K. J. & Fisher, A. C. Environmental Preservation, Uncertainty, and Irreversibility. *Q. J. Econ.* **88**, 312 (1974).

28. Dixit, A. K. & Pindyck, R. S. *Investment under uncertainty*. (Princeton University Press, 1994).

29. Markowitz, H. Portfolio Selection. *J. Finance* **7**, 77 (1952).

30. Sharpe, W. F. Capital Asset Prices: A Theory of Market Equilibrium under Conditions of Risk. *J. Finance* **19**, 425 (1964).

31. Cifdaloz, O., Regmi, A., Anderies, J. M. & Rodriguez, A. A. Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: The Pumpa Irrigation System in Nepal. *Ecol. Soc.* **15**, art39 (2010).

32. Levin, S. A. *et al.* Governance in the Face of Extreme Events: Lessons from Evolutionary Processes for Structuring Interventions, and the Need to Go Beyond. *Ecosystems* **25**, 697–711 (2022).

33. Peterson, G., Allen, C. R. & Holling, C. S. Original Articles: Ecological Resilience, Biodiversity, and Scale. *Ecosystems* **1**, 6–18 (1998).

34. Nyström, M. Redundancy and response diversity of functional groups: implications for the resilience of coral reefs. *Ambio* **35**, 30–35 (2006).

35. Kummu, M. *et al.* Interplay of trade and food system resilience: Gains on supply diversity over time at the cost of trade independency. *Glob. Food Secur.* **24**, 100360 (2020).

36. Hedblom, M., Andersson, E. & Borgström, S. Flexible land-use and undefined governance: From threats to potentials in peri-urban landscape planning. *Land Use Policy* **63**, 523–527 (2017).

37. Haldane. Rethinking the Financial Network - speech by Andy Haldane. https://www.bankofengland.co.uk/speech/2009/rethinking-the-financial-network (2009).

38. Haldane, A. G. & May, R. M. Systemic risk in banking ecosystems. *Nature* **469**, 351–355 (2011).

39. Carpenter, S. R., Brock, W. A., Folke, C., van Nes, E. H. & Scheffer, M. Allowing variance may enlarge the safe operating space for exploited ecosystems. *Proc. Natl. Acad. Sci.* **112**, 14384–14389 (2015).

40. Khoury, C. K. *et al.* Increasing homogeneity in global food supplies and the implications for food security. *Proc. Natl. Acad. Sci.* **111**, 4001–4006 (2014).

41. Hendrickson, M. K. Resilience in a concentrated and consolidated food system. *J. Environ. Stud. Sci.* **5**, 418–431 (2015).

42. Öborn, I. *et al.* Restoring Rangelands for Nutrition and Health for Humans and Livestock. in *The XXIV International Grassland Congress / XI International Rangeland Congress (Sustainable Use of Gr Use of Grassland and Rangeland Resour assland and Rangeland Resources for Impr ces for Improved Livelihoods)* (2022).

43. Commission, corporateName:Productivity. Vulnerable Supply Chains - Productivity Commission Interim Report. https://www.pc.gov.au/inquiries/completed/supply-chains/interim (2021).

44. Mouillot, D., Graham, N. A. J., Villéger, S., Mason, N. W. H. & Bellwood, D. R. A functional approach reveals community responses to disturbances. *Trends Ecol. Evol.* **28**, 167–177 (2013).

45. Leslie, P. & McCabe, J. T. Response Diversity and Resilience in Social-Ecological Systems. *Curr. Anthropol.* **54**, 114–143 (2013).

46. Biggs, R. *et al.* Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annu. Rev. Environ. Resour.* **37**, 421–448 (2012).

47. Anderies, J. M. Managing variance: Key policy challenges for the Anthropocene. *Proc. Natl. Acad. Sci.* **112**, 14402–14403 (2015).

48. Csete, M. E. & Doyle, J. C. Reverse Engineering of Biological Complexity. *Science* **295**, 1664–1669 (2002).

49. Carlson, J. M. & Doyle, J. Highly Optimized Tolerance: Robustness and Design in Complex Systems. *Phys. Rev. Lett.* **84**, 2529–2532 (2000).

50. Kitano, H. Biological robustness. *Nat. Rev. Genet.* **5**, 826–837 (2004).

51. Csete, M. & Doyle, J. Bow ties, metabolism and disease. *Trends Biotechnol.* **22**, 446–450 (2004).

52. Anderies, J. M., Rodriguez, A. A., Janssen, M. A. & Cifdaloz, O. Panaceas, uncertainty, and the robust control framework in sustainability science. *Proc. Natl. Acad. Sci.* **104**, 15194–15199 (2007).

53. Rodriguez, A. A., Cifdaloz, O., Anderies, J. M., Janssen, M. A. & Dickeson, J. Confronting Management Challenges in Highly Uncertain Natural Resource Systems: a Robustness–Vulnerability Trade-off Approach. *Environ. Model. Assess.* **16**, 15–36 (2011).

54. Charpentier, A. Insurability of Climate Risks. *Geneva Pap. Risk Insur. - Issues Pract.* **33**, 91–109 (2008).

55. Alfieri, L., Feyen, L. & Di Baldassarre, G. Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Clim. Change* **136**, 507–521 (2016).

56. Isakson, S. R. Derivatives for Development? Small-Farmer Vulnerability and the Financialization of Climate Risk Management: Small-Farmer Vulnerability and Financialization. *J. Agrar. Change* **15**, 569–580 (2015).

57. Müller, B. & Kreuer, D. Ecologists Should Care about Insurance, too. *Trends Ecol. Evol.* **31**, 1–2 (2016).

58. Walker, B. *et al.* Looming Global-Scale Failures and Missing Institutions. *Science* **325**, 1345–1346 (2009).

59. Berkes, F. *et al.* Globalization, Roving Bandits, and Marine Resources. *Science* **311**, 1557–1558 (2006).

60. Walker, B. H., Langridge, J. L. & McFARLANE, F. Resilience of an Australian savanna grassland to selective and non-selective perturbations. *Austral Ecol.* **22**, 125–135 (1997).

61. Polasky, S. *et al.* Corridors of clarity: Four principles to overcome uncertainty paralysis in the anthropocene. *BioScience* **70**, 1139–1144 (2020).

62. Engström, G. *et al.* Carbon pricing and planetary boundaries. *Nat. Commun.* **11**, 4688 (2020).

63. Sun, J. C., Ugolini, S. & Vivier, E. Immunological memory within the innate immune system. *EMBO J.* embj.201387651 (2014) doi:10.1002/embj.201387651.

64. Vély, F. *et al.* Evidence of innate lymphoid cell redundancy in humans. *Nat. Immunol.* **17**, 1291–1299 (2016).

65. Grimm, N., Cook, E., Hale, R. & Iwaniec, D. A broader framing of ecosystem services in cities. in (2015). doi:10.4324/9781315849256.CH14.

66. Jiang, B., Mak, C. N. S., Zhong, H., Larsen, L. & Webster, C. J. From Broken Windows to Perceived Routine Activities: Examining Impacts of Environmental Interventions on Perceived Safety of Urban Alleys. *Front. Psychol.* **9**, 2450 (2018).

67. Andersson, E. *et al.* Urban climate resilience through hybrid infrastructure. *Curr. Opin. Environ. Sustain.* **55**, 101158 (2022).

68. Douglas, M. & Wildavsky, A. *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. (University of California Press, 1983).

69. Weber, E. U., Ames, D. R. & Blais, A.-R. 'How Do I Choose Thee? Let me Count the Ways': A Textual Analysis of Similarities and Differences in Modes of Decision-making in China and the United States. *Manag. Organ. Rev.* **1**, 87–118 (2005).

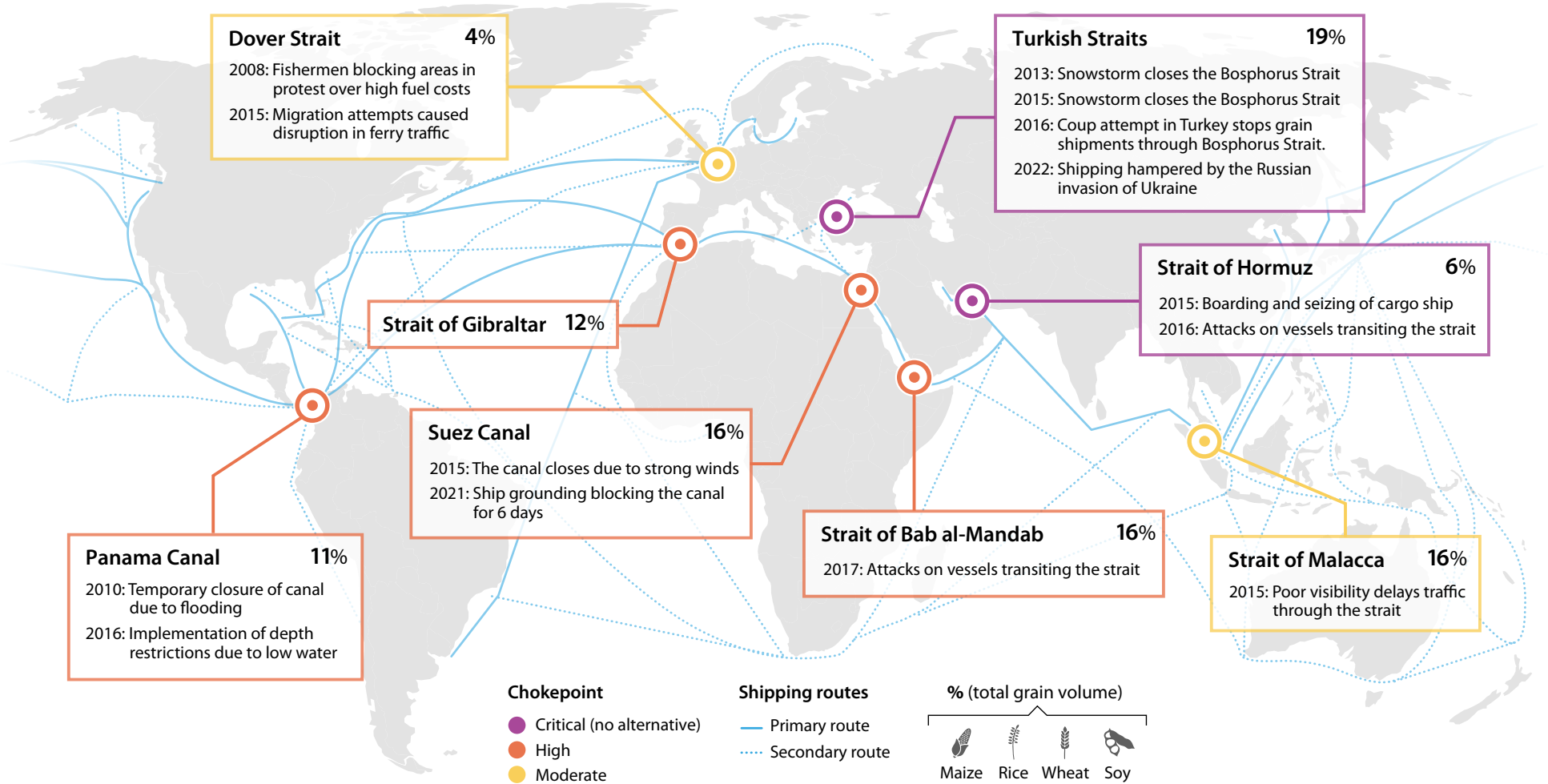
70. Kunreuther H., S. Gupta, V. Bosetti, R. Cooke, V. Dutt, M. Ha-Duong, H. Held, J. Llanes-Regueiro, A. Patt, E. Shittu, and E. & Weber. *Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter2.pdf (2014).

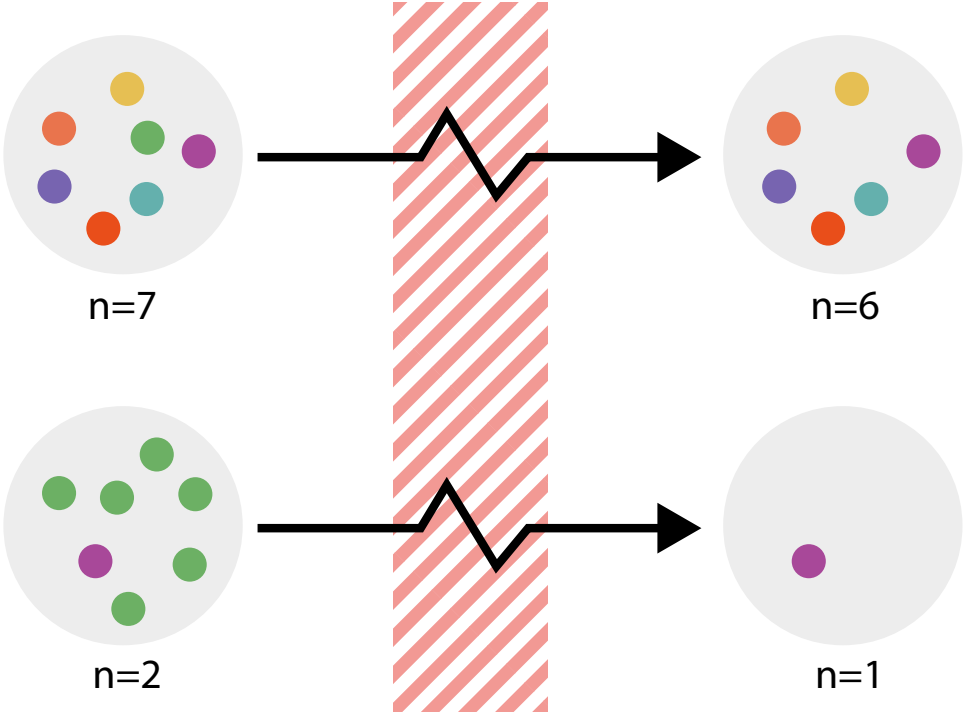
71. Meadows, D. H. *Thinking in systems: a primer*. (Earthscan, 2009).

72. Nyborg, K. *et al.* Social norms as solutions. *Science* **354**, 42–43 (2016).

73. *Social resilience in the neo-liberal era*. (Cambridge University Press, 2013).

74. Norström, A. V. *et al.* Principles for knowledge co-production in sustainability research. *Nat. Sustain.* **3**, 182–190 (2020).


Dover Strait 4%
2008: Fishermen blocking areas in protest over high fuel costs
2015: Migration attempts caused disruption in ferry traffic
Turkish Straits 19%
2013: Snowstorm closes the Bosphorus Strait
2015: Snowstorm closes the Bosphorus Strait
2016: Coup attempt in Turkey stops grain shipments through Bosphorus Strait.
2022: Shipping hampered by the Russian invasion of Ukraine
Strait of Hormuz 6%
2015: Boarding and seizing of cargo ship
2016: Attacks on vessels transiting the strait
Strait of Gibraltar 12%
Suez Canal 16%
2015: The canal closes due to strong winds
2021: Ship grounding blocking the canal for 6 days
Strait of Bab al-Mandab 16%
2017: Attacks on vessels transiting the strait
Strait of Malacca 16%
2015: Poor visibility delays traffic through the strait
Panama Canal 11%
2010: Temporary closure of canal due to flooding
2016: Implementation of depth restrictions due to low water
Chokepoint
Critical (no alternative)
High
Moderate
Shipping routes
Primary route
Secondary route
% (total grain volume)
Maize
Rice
Wheat
Soy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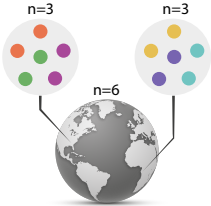
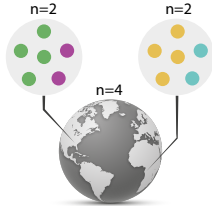


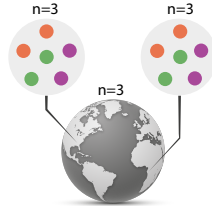
High local, high global (beta-) response diversity

Low risk for abrupt change at local scale and global (cascading) response.



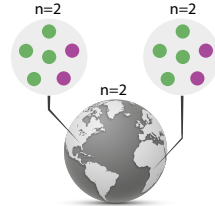
Low local, high global (beta-) response diversity

High risk for abrupt change at local scale, but limited risk for global (cascading) response.



High local, low global (beta-) response diversity

Areas are becoming more similar (homogenization). Increased risk for a synchronized change at global scale.



Low local, low global (beta-) response diversity

High risk for synchronized abrupt change at local and global scales.