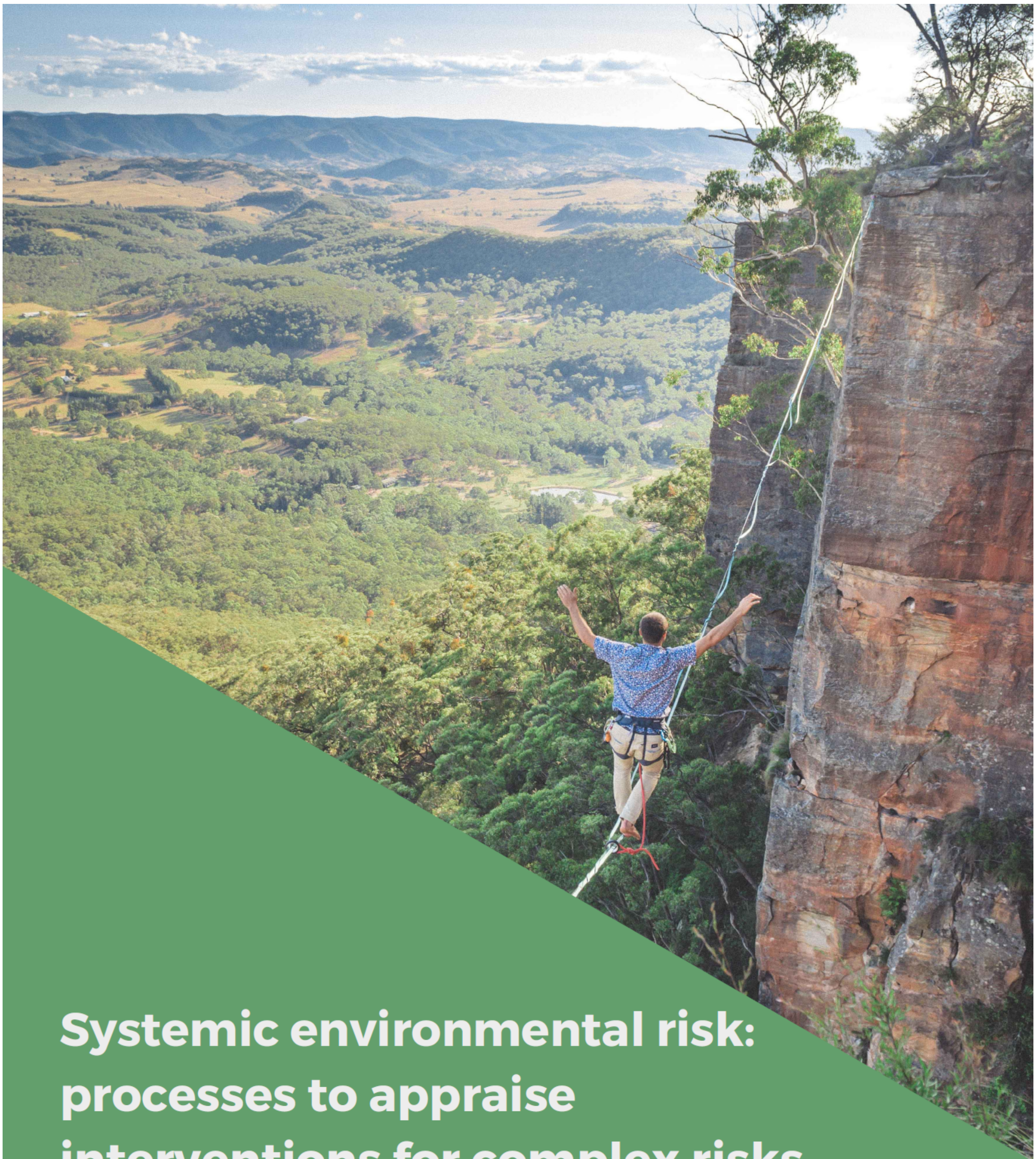

Systemic environmental risk: processes to appraise interventions for complex risks

SysRisk Final Report
December 2021

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We thank the following expert participants for their involvement in workshops to identify different risk cascades and to identify and appraise interventions to reduce systemic risk.

Air Quality

- Jo Barnes, University of the West of England Bristol
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- Melville Miles, Greencore
- Maddy Power, University of York
- Ben Raskin, Soil Association
- Yaadwinder Sidhu, Defra
- Alastair Trickett, Trickett Farming

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Executive summary

Rationale

- Systemic risks are complex risks arising from interactions between different interconnected systems; for example, through a process of contagion across political, economic, social, technological, legal/regulatory or environmental systems. These risks are likely to become more severe under a range of global change drivers, such as increasing population size, resource use, biodiversity loss and climate change.
- The highly complex nature of these risks prevents probabilistic assessment as is carried out for more conventional risks. Therefore, they have tended to be neglected in risk management.

Process

- This project explores a new approach based on qualitative participatory systems mapping to help appraise these risks and identify 'watchpoints' to track their progress. We focus on three case studies: air quality, biosecurity and food security
- We identify a broad range of interventions to reduce risk, exploring systems approaches to help prioritise these interventions; for example, understanding co-benefits in terms of reducing multiple different types or risk, as well as understanding trade-offs.

Outcomes

- We involved 36 experts in our participatory systems mapping, selected in a stratified way to cover a range of backgrounds, plus 14 members of the interdisciplinary project team. Across seven workshops, we identified 39 'risk cascades', defined as pathways by which systemic risk can have negative impacts on human health, and we identified 681 watchpoints and interventions.

Key recommendations

This report takes a reflective approach, critically discussing constraints and refinements to the experimental process. Building from the lessons learned, this overall recommendation is made:

To deal with systemic environmental risk, we recommend a participatory systems mapping approach with inputs from diverse experts to identify interventions, then a follow up process using a systems approach to understand key considerations of the interventions to assist with their prioritisation.

Summary of additional recommendations:

Participant selection

- Recruiting experts in a stratified way to enhance cognitive diversity

Online working

- Running workshops online and using interactive software

Participatory systems mapping

- Using a broad qualitative approach to ensure that key pathways by which risks propagate through socioenvironmental systems are not neglected
- Prior work to set the boundaries for analysis before developing risk cascades

Futures approaches

- Using explicit futures methods to overcome cognitive biases
- Identifying system 'watchpoints' to build effective monitoring capacity

Dealing with uncertainty

- Complementing risk appraisal with general resilience building

Refining interventions

- Combining with additional systems approaches to help prioritise interventions

Institutional capacity

- Taking these recommendations forwards will require a significant investment in systemic risk appraisal capacity

Introduction

What is systemic risk?

Some risks are well defined and play out in a familiar and consistent way, making them more predictable. These recognisable patterns enable targeted management to reduce risk. For example, workplace accidents have been extensively reduced through the application of health and safety procedures in many countries. Beyond such 'conventional' risks, other types of risk are less intuitive and result from non-linear cause and effect relationships, often manifesting themselves through complex causal pathways. These 'systemic' risks arise from interactions between different interconnected systems, for example through a process of contagion across political, economic, social, technological, legal/regulatory or environmental systems (Centeno et al., 2015; IRGC, 2018). Climate change is an example of a driver commonly involved in systemic risks, potentially impacting the health and prosperity of society and environmental systems in a myriad of complex ways.

Systemic risks present challenges in terms of understanding their importance (e.g. their probability and impact) and developing appropriate responses. Anticipatory frameworks are challenging due to the complex nature of causal pathways, leading to low confidence and/or deep uncertainty inherent in such assessments. Nevertheless, appraising systemic risks is essential because these risks can have extensive impacts on the health and prosperity of our societies. In an increasingly interconnected world, systemic risks are becoming more likely, thus increasing the urgency for credible and robust frameworks to deal with them. Innovative frameworks and decision-making support tools are needed to identify strategies to reduce exposure and impact from such risks (IRGC, 2015). In addition to these innovations, humility is recommended to recognise the deep uncertainty in the dynamics of complex social-environmental systems, maintaining the need to develop general resilience building in addition to reductionist risk assessment (e.g. NPC, 2020).

Environmental systemic risks in an increasingly interconnected world

Increasing globalisation in terms of economy, finance, technology systems and social networks leads to an amplification of potential risk pathways. Furthermore, as we place increasing strain on global ecosystems through habitat degradation and pollution (IPBES, 2019; EEA, 2020a), and as certain resources become more scarce, the environmental base supporting our economies and societies becomes weaker, further increasing systemic risk.

This report focuses on systemic risk mediated through the environment (e.g. Figure 1). Eight of the top ten global risks identified by the World Economic Forum involve the environment (WEF, 2020), yet there is often limited awareness of this type of risk. This has been starkly highlighted by the Covid-19 pandemic (Hilton & Baylon, 2020) and remains highly relevant for strategic socioeconomic recovery efforts. More than 60% of emerging human disease is zoonotic in origin (Allen et al., 2017; Taylor et al., 2001) and emergence is made more likely by global environmental degradation (IPBES, 2020). Disease impacts can be exacerbated by environmental factors like air quality (Bourdrel et al. 2021) and some of the knock-on consequences of pandemics, such as food insecurity, are clearly tied to environmental factors. These interlinkages are recognised in the One Health research agenda (WHO, 2021a).

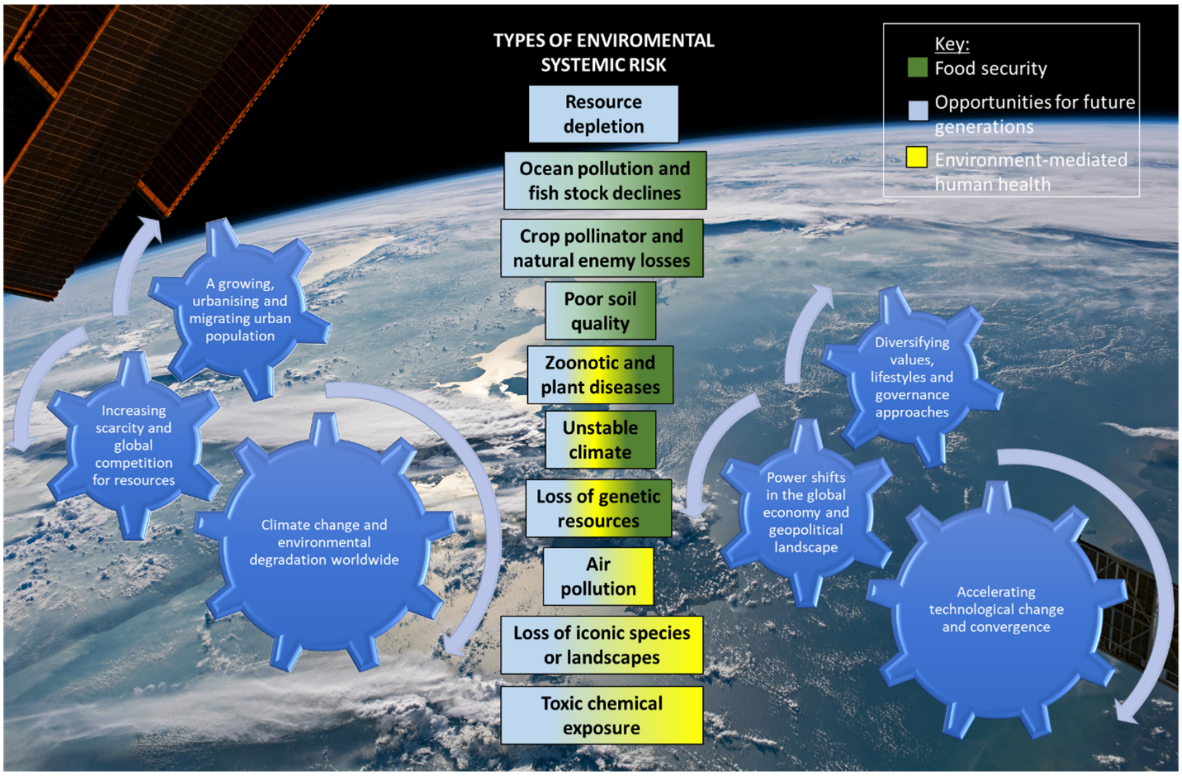


Figure 1, *Various types of environmental systemic risk that threaten food security, opportunities for future generations and human health. The risks are impacted by a complex set of interacting drivers of change (these specific drivers sourced from a European Environment Agency report;* EEA, 2020b*). Image credit: NASA.*

Some environmental systemic risks might be expected to play out, or become increasingly extreme, over longer timescales. For example, the impacts of climate change on populations in some countries like the UK are still limited, versus projections for mid-century onwards. Equally, some systemic risks have lower probability (over a given time period) but would have very high impact (Blong, 2021). These include 'global catastrophic risks' such as an inability to grow crops as a result of a nuclear winter. These types of risk may be exacerbated by a gradual loss of resilience of a socio-environmental system (Biggs et al. 2012); for example, through the degradation of natural, social and financial capital. This erosion of resilience can lead to sudden 'tipping points' in terms of a change in state (e.g. Folke et al., 2004; Ritchie et al. 2021). These involve amplifying effects leading to tipping points as a combination of relatively small forces which can trigger compounding, potentially irreversible stresses (Farmer, 2019). This has been recognised as an important factor in systemic risk analysis (Hendricks, 2009). However, we do not limit our definition of systemic risk to only involving sudden 'tipping points' (e.g. as in Hendricks, 2009), nor do we limit our definition to necessarily involving the probability of breakdowns in an entire system (which is not well defined and likely to be rare; Kaufman & Scott, 2003). Instead, we adopt a broader definition based on the threat that individual failures, accidents, or disruptions present to a system through the process of contagion (Centeno et al., 2015; IGRC, 2018). This broader definition captures threats like air pollution, food insecurity and biosecurity that have more limited impacts (i.e. not causing 'whole-system breakdown' cf. Kaufman & Scott, 2003). These risks are being realised already, and are particularly salient in light of Covid-19. Therefore, this project focuses on three salient case studies (Figure 2), but with the strong caveat that there are more environmental systemic risks which also need to be appraised in detail (e.g. Figure 1).

Air Quality: reducing health impacts of air pollution
Biosecurity: improving resilience to zoonotic disease emergence
Food Security: ensuring access to healthy, safe, affordable food

Figure 2, *The three case studies explored in the SysRisk process*

Going beyond the status quo in risk management

Several academic and science-policy initiatives have highlighted how risks can cascade in complex socio-environmental systems impacting livelihoods, health, social cohesion and the environment (Sutherland & Woodroof 2009; Reynolds 2013; Centeno et al. 2015; Avin et al. 2018). Yet, major deficits remain in many governmental risk management procedures to deal with systemic risk (IRGC 2011; GmbH 2015; IRGC 2015; Hilton & Baylon, 2020; House of Lords, 2021). These deficits relate to both assessing and understanding risks (e.g. gathering and interpreting knowledge around hazard probabilities and consequences including multiple dimensions of risk, and how risks are perceived by stakeholders depending on values, beliefs, interests). They also pertain to managing risks (e.g. failure to consider a reasonable range of risk mitigation options, inability to reconcile the timeframe of risk with decision making procedures, failure to balance transparency and confidentiality, and failure to build adequate and coherent organisational capacity to manage risk).

A wide range of institutions face these challenges, including national governments as well as multilateral risk management initiatives (e.g. UN Sendai Disaster Risk Framework; International Risk Governance Center, World Health Organisation, etc.). It is clear that understanding and responding to systemic risks will require diverse expertise across sectors/disciplines, and requires disciplines which go beyond traditional risk management approaches by introducing new competencies and approaches, such as systems thinking literacy (Ison & Shelley, 2016; Oliver et al. 2021).

There is a strong potential for risk managers (e.g. in government and other policymakers) to draw more strongly upon the diverse expertise available in academic institutions, other sectors and public community groups to span the required breadth of multi-disciplinary input. This SysRisk project explores a possible process by which systemic risks can be appraised, with relevant interventions and key 'watchpoints' identified to understand if and how risks are being realised. The process is experimental and therefore this report takes a reflexive approach to understand the possible strengths and limitations of the methodology, with a view to informing future refinements.

SysRisk process and project materials

The SysRisk process is described in brief here, with further details found in the report Appendix. Below, we include an infographic of SysRisk project materials and outputs (Figure 3), visualisation of key activities (Figures 4) and summarised descriptions of these activities in sections below.

Figure 3, *Infographic of SysRisk project materials and outputs*

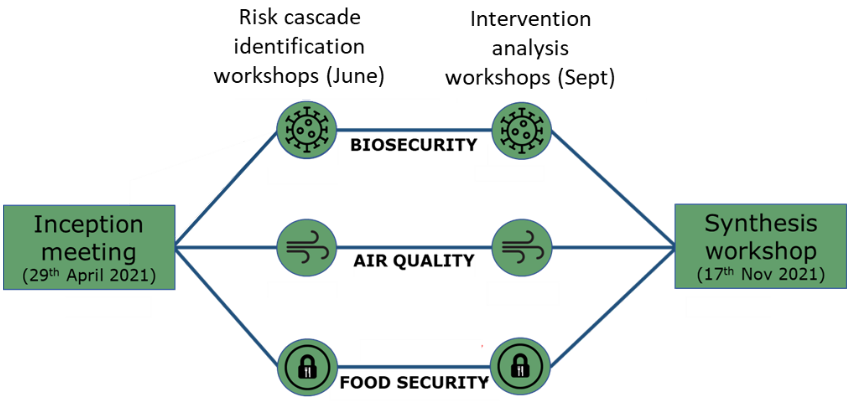


Figure 4, *Overview of participatory expert process*

Selection of expert participants

To maximise cognitive diversity for different aspects of socio-environmental systems, for each case study, a longlist of potential participants was developed by identifying people with expertise in either the Political, Economic, Social, Technological, Legal/regulatory and Environmental (PESTLE) aspects of their case study area (Figure 5; and see Participant Selection section for further reflections). Participants were contacted via email with an invitation and information sheet and asked to return a consent form if they wished to take part. Twelve participants were initially recruited to each case study. On occasions where participants had to drop out of the project (7 participants withdrew from the process across the three case studies), additional experts were recruited to retain a balance of expertise across the six PESTLE categories. Anonymity of identity and affiliation of participants was not offered, because this was an expert elicitation study where participants are co-creators of the research and invited to co-author some outputs. However, meetings and workshops were conducted according to the 'Chatham house rule', where any information shared at the workshop retained anonymity. Discussions during meetings were not audio-visually recorded, but notes were taken by members of the SysRisk team that were only available to SysRisk team members. Ethical approval from a University Ethics committee was received prior to the work commencing.

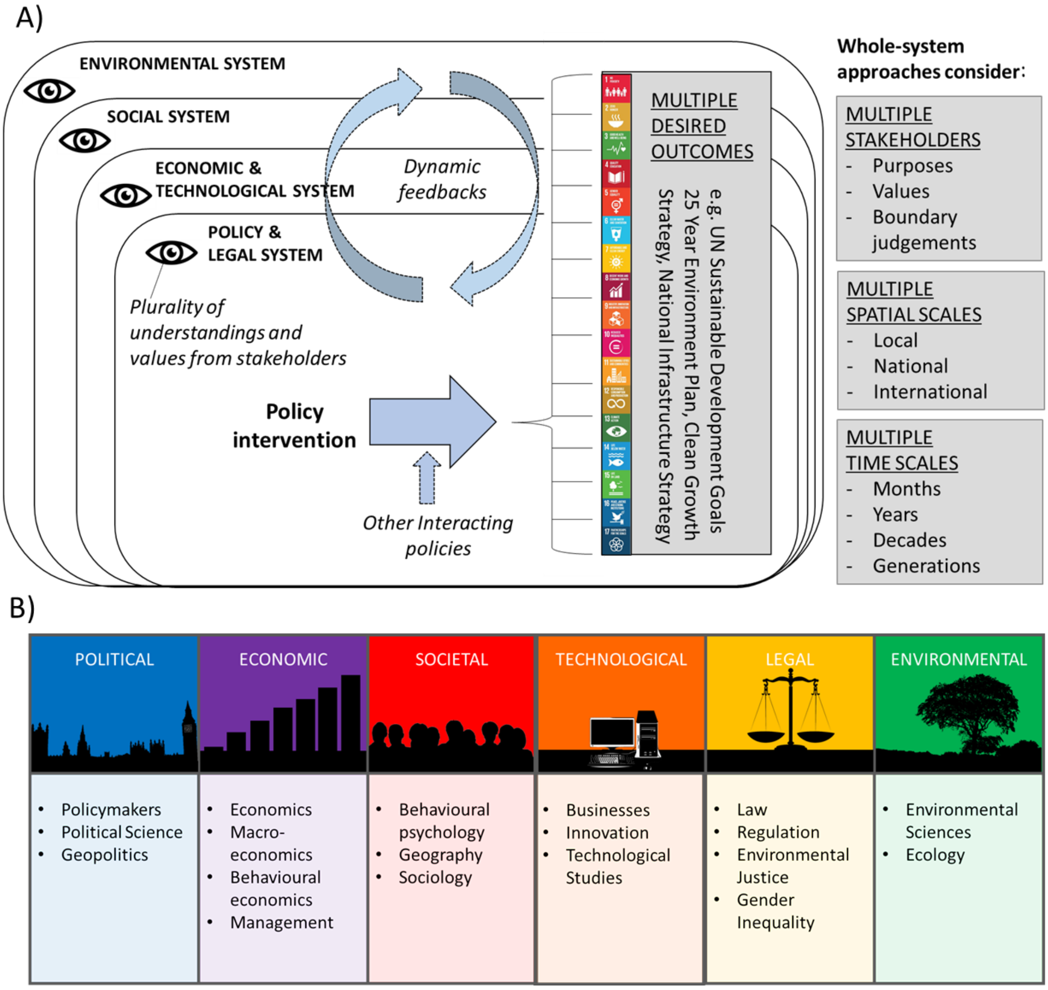


Figure 5, *Key elements of a 'systems approach' important for addressing systemic risk (panel A; reproduced from Oliver et al., 2021). Using this in the project participants were selected in a stratified way to cover six 'PESTLE' categories, shown in panel B with example disciplines.*

PRSM, the Participatory System Mapping software used in the workshops

The project contributed to the development of the Participatory System Mapper (PRSM). PRSM is an app that makes it easy to draw networks (or 'maps') of systems, working together collaboratively. Using PRSM, groups of people, each with their own computer (or tablet) can collaborate in the drawing of a map. They may be sitting around a table, discussing the map as it is created face to face, or working remotely, using video conferencing or the chat feature that is built into the app. Everyone can participate because every edit (creating nodes and links, arranging them, annotating them, and so on) is broadcast to all the other participants as the changes are made.

PRSM runs in a web browser on a desktop PC or a tablet. When someone starts PRSM in their browser, a 'room' is created in which to draw the network. Other users can join this room to share the work. Only those with access to the room can see what is being created.

The network or map can be anything that has items (or 'factors' or 'nodes') connected by links (or 'edges'). For this project, the items were causal factors linked in a risk 'cascade', with interventions to reduce risk and watchpoints to monitor risk. Each item, and the links between them, can have an annotation attached to describe the factor or link in more detail, or to reference other documents.

As a result of our experience in using PRSM during the project workshops, several new features were added to the software. PRSM continues to be developed and is freely available and open source (see https://prsm.uk)

Workshop 1: Development of risk cascades

Ahead of the first workshops, participants were asked to provide three short narratives or visual flow charts outlining potential 'risk cascades' that could result in health impacts to the UK, relating to their subject area. We define a risk cascade as a scenario of events linked in a causal chain that leads to some impact (on health in this case). These were mostly linear but they could also include exacerbating factors (sometimes referred to elsewhere as 'threat multipliers'). Later in the process we added watchpoints and interventions to track and reduce risk respectively. A generic example is shown in Figure 6, and a specific example can be found in the Appendix (Figure A2). There were instructions to optionally use Participatory System Mapper (PRSM) software to draw the cascades (Figure 6). Each case study received multiple risk cascades from participants (see Appendix for details). These were supplemented by cascades provided by members of the SysRisk team with relevant subject knowledge. Many of the cascades were highly interconnected, and were edited and amalgamated by the SysRisk team to produce maps grouped by broad themes, each containing multiple cascades. Finally, short narratives were written describing each particular risk cascade pathway included in the maps (see Project output directory).

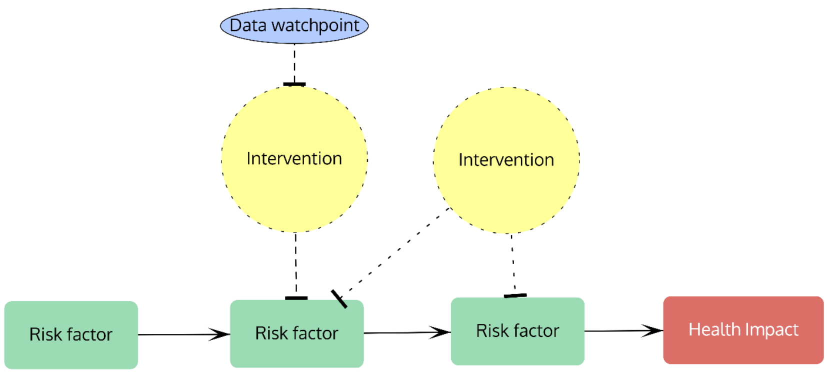


Figure 6, *Generic elements of the 'risk cascades' developed by participatory mapping. Causal pathways by which risks flow through political, economic, social, technological, legal/regulatory and environmental spheres are shown in green. The final impact on UK citizen health is shown in red. Interventions to reduce risks are shown in yellow along with data/monitoring initiative 'watchpoints' in blue, which can help track whether a specific risk cascade is being realised.*

At the workshop itself (a separate workshop was run for each case study, Figure 4), participants were asked to comment on and edit the factors and connections on the maps to improve accuracy and clarity. Then they added interventions (actions to reduce risk) and data watchpoints (data sources/monitoring schemes for adaptive risk governance) to the maps (Figure 6). These were added initially individually, then there was time to discuss and edit all the interventions and data watchpoints.

After the workshop the SysRisk team amalgamated duplicate interventions and provided more depth and background information. The risk cascades and overview maps were also adapted following participant inputs during the workshop. For the food case study, specific recommendations from the National Food Strategy (Dimbleby, 2021) were also included as interventions. These were either related to interventions added by participants, or subjects raised during the workshop discussion. For links to all the risk cascade maps and narratives see the Project output directory section.

Workshop 2: Considering interventions in greater depth

In preparation for workshop 2, using scores from participants, the SysRisk team carried out an analysis of the risk narratives to derive a rank order based on impact and likelihood (Figure 7; additional detail in Appendix). The results of this exercise were used to select four narratives from each case study that scored highly for impact and likelihood for further exploration in the second workshop.

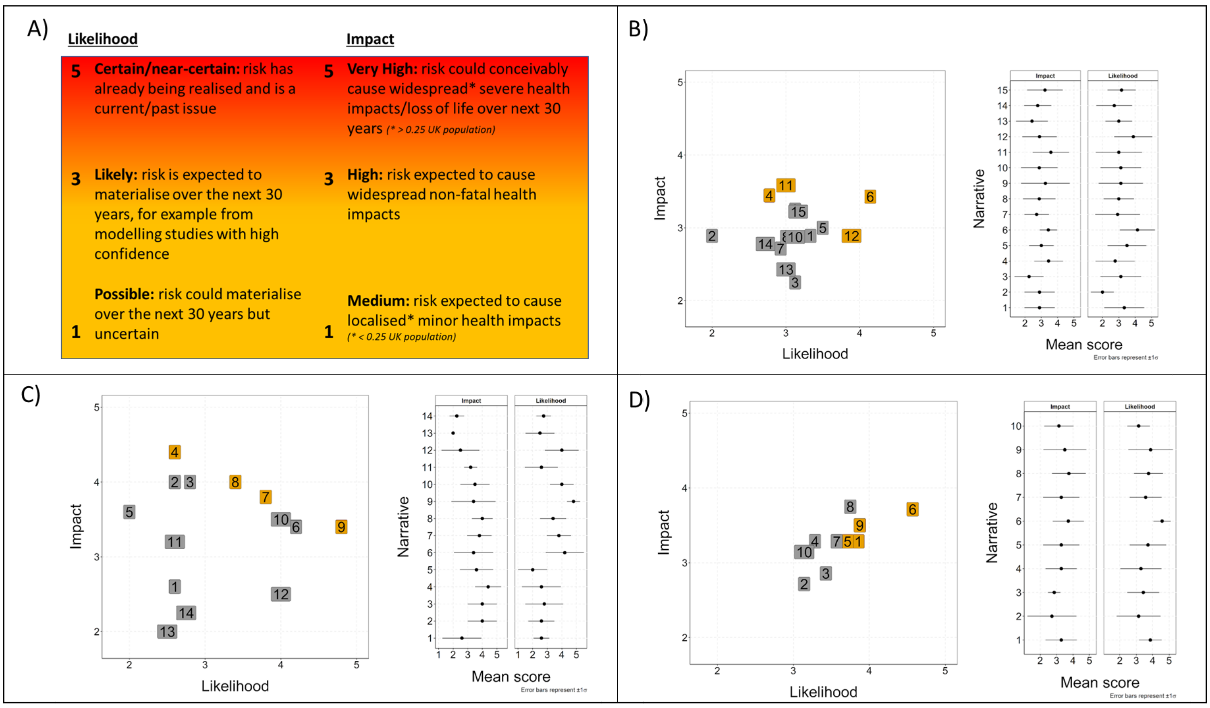


Figure 7, *Scoring criteria for assessing the likelihood and impact of specific risk cascades (panel A). Mean scores and standard deviations as assessed by participants for air quality (B) biosecurity (C) and food security (D) case studies. Cascades selected for workshop 2 are highlighted in orange.*

Cascade numbers: **Air Quality (panel B)** 1. Weight, 2. Perception, 3. Scavenging, 4. Uptake, 5. Temperature Effects, 6. Extreme Weather, 7. Net-Zero Pressure, 8. Financial Pressure, 9. Government Resources, 10. NHS Pressure, 11. Novel Pollutants, 12. Domestic Emissions, 13. Delivery Vehicles, 14. Domestic Energy, 15. Pollution Resilience; **Biosecurity (panel C)** 1. Dormant Pathogen, 2. Resource Prioritisation, 3. Novel Research, 4. Malicious Actors, 5. Sample Transport, 6. Food-borne Pathogens, 7. Livestock, 8. Wildlife, 9. Household Transmission, 10. Physical and Mental Health, 11. Vaccine Uptake, 12. School Closures, 13. Gender Gaps, 14. Public Health Messaging; **Food Security (panel D)** 1. Soil Health Decline, 2. Water Risks (shortages and floods), 3. Crop Pests and Diseases, 4. Policy and Economic Impacts on UK Land Use, 5. Non-tariff Trade Barriers, 6. Labour Shortages, 7. Trade Deals and Retailer-Grower Power Relationships, 8. Human Transmissible Disease, 9. Impact of System Shocks Such as the Pandemic Given Increased Reliance on Food Aid, 10. Livestock Disease with Human Health Impacts.

In workshop 2 itself (a separate workshop for each case study, Figure 4), participants were invited to assess the four prioritised cascades (Figure 7) and review the previously identified interventions. Participants were split into two break out groups, with each group covering two of the four prioritised cascades. Each group was given time to study the PRSM maps and previously identified interventions and suggest any further amendments required. Discussions were then structured by facilitators to answer the following questions:

1. *If all these interventions were in place to what extent would the risk be effectively reduced?*
2. *Are multiple complementary interventions needed?*
3. *In aggregate, what are the main barriers to putting effective interventions in place?*
4. *Are there unintended consequences of these interventions (or positive co-benefits)?*

Following the second workshop, the risk cascades and narratives were again reviewed and rewritten by the SysRisk team, incorporating the comments and suggestions made by participants, to derive final versions, with their relevant interventions (see Project output directory).

Synthesis Workshop - Assessing multifunctionality and implementation of interventions

The third participatory workshop was developed to explore protocols to help refine how certain interventions might be implemented. There were two elements: i) understanding which interventions would be effective for addressing multiple types of risk (termed hereon 'multifunctional' interventions), and ii) how to implement broad interventions which are formulated in quite vague terms. To achieve this, each of the interventions described in the final narratives/risk cascades were assessed, initially by members of the SysRisk team, and then by participants, to determine their levels of multifunctionality and implementation. Multifunctionality, in this sense, was defined as the ability of an intervention to simultaneously impact the other case studies, either as a co-benefit or a trade-off. This assessment was in two phases. First, individuals scored interventions from their own case study with regards to the extent they were being implemented using the following criteria:

- **Yes**: Existing policy framework in place, and/or significant business of third sector initiatives deemed to have significant impact.
- **Partly**: Part of current policy reform or planned initiatives; some initiatives in place by businesses/third sector.
- **No**: Some recognition of the problem and discussion of possible actions but negligible co-ordinated implementation.

Second, individuals reviewed interventions from the two other case studies to assess whether any of these interventions would have an impact on their own case study (i.e. their multifunctionality; Figure 8). For example, would interventions identified in the air quality case study have benefits or trade offs for food security or biosecurity. Each intervention was given one of the following scores: -2 (strong trade off), -1 (weak trade off), 0 (no/very limited effect/s), 1 (weak co-benefit), 2 (strong co-benefit). Where intervention impact was deemed to be highly context dependent an asterisk was added to the number, e.g. 2*. Participants were invited to add comments if they felt their scoring required justification or explanation and were also given the option of leaving interventions blank if they felt it was outside of their subject knowledge.

These interventions were further reviewed in the third workshop. In case study specific groups participants used the software Mural to develop implementation strategies for a single multifunctional intervention. The exercise involved describing specific ways to implement the respective interventions, along with identification of enablers and barriers for implementation, potential negative impacts, who are the actors and stakeholders responsible for implementation, and winners and losers if the intervention was implemented.

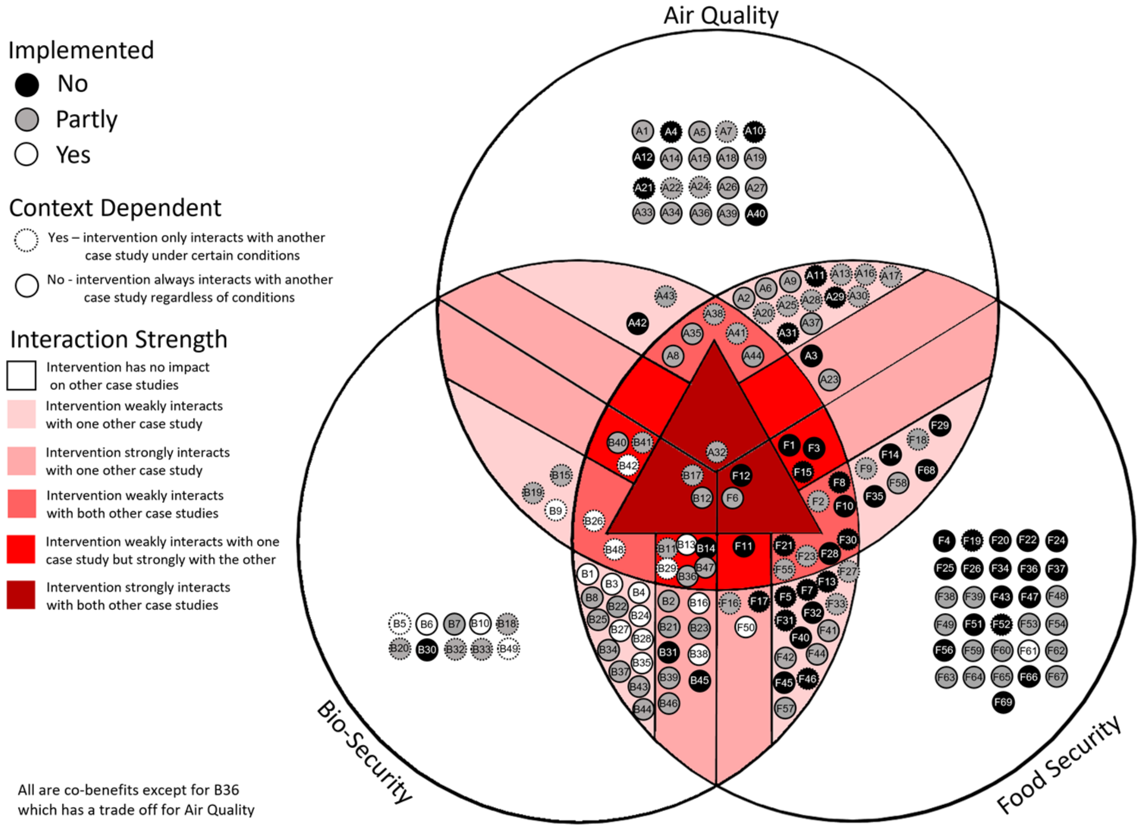


Figure 8, *Visualisation of the estimated degree of multifunctionality of interventions across the three case studies along with degree of current implementation. Interventions listed in the centre of the Venn diagram have multiple benefits in terms of reducing multiple types of risk across the case studies. The intervention identity is shown by a code within each circle and can be found in Tables A2, A3 and A4 in the Appendix).*

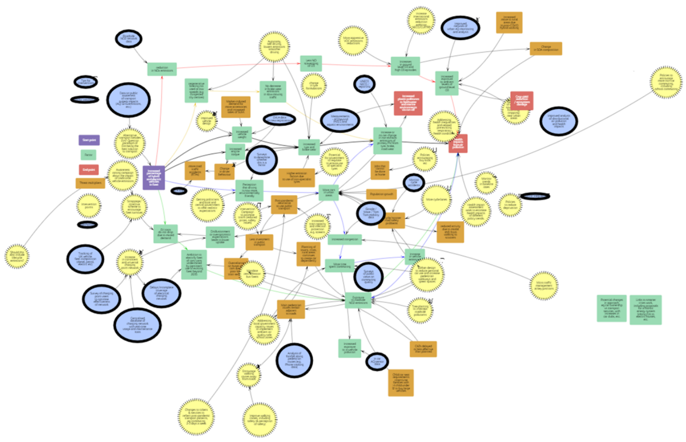
Project output directory

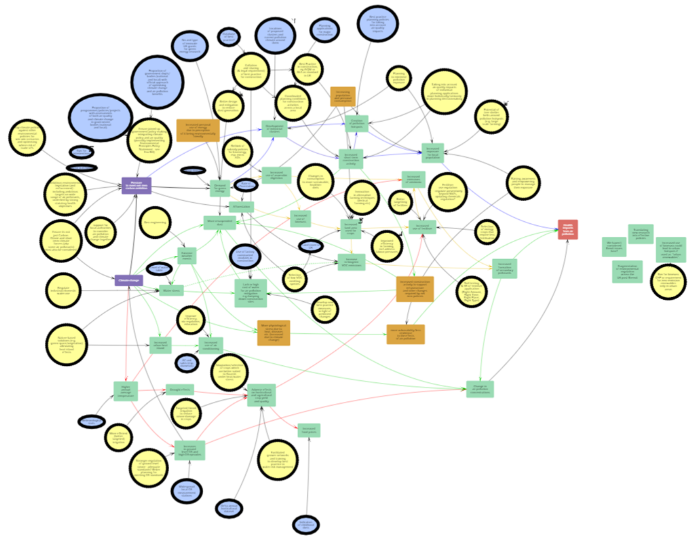
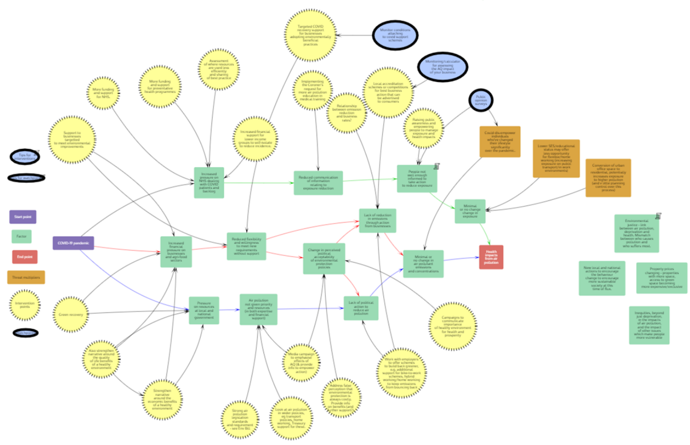
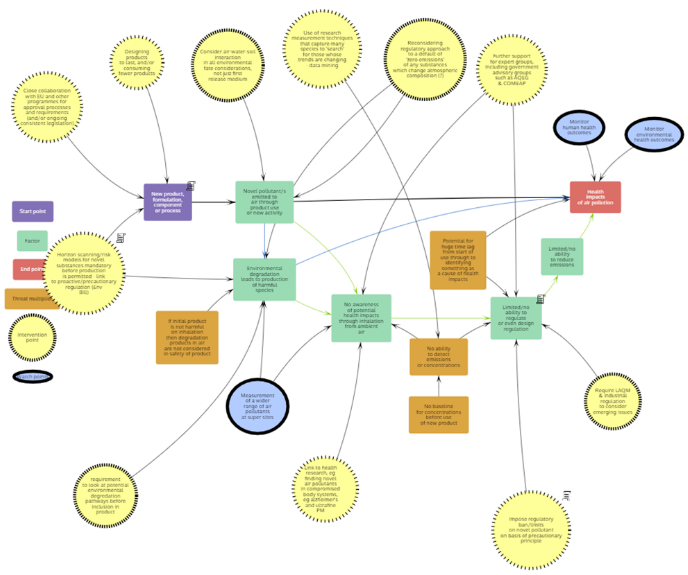
Detailed below in Tables 1-3 are hyperlinks to read-only versions of the risk cascade maps (in the PRSM software), narratives of risk in prose and overview theme maps (that show how individual risk cascades fit together).

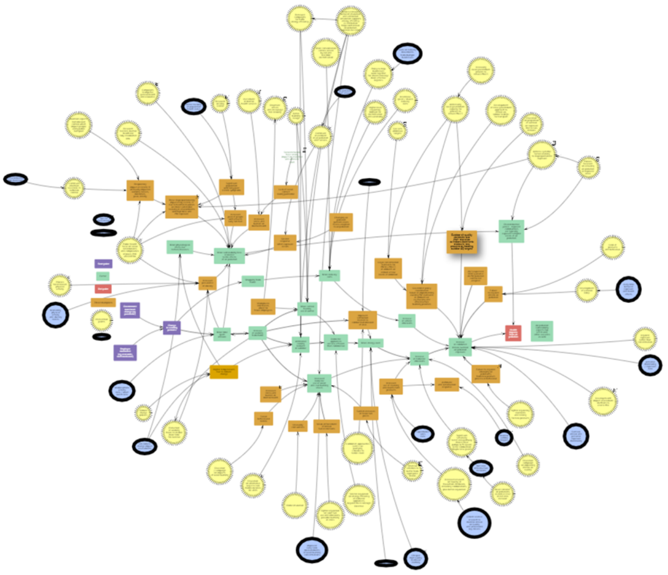
Air Quality

The SysRisk participatory process resulted in 15 individual risk cascades for how air quality linked to human health with accompanying narratives (Table 1). The four individual risk cascades prioritised as having high likelihood and impact, that were further examined in workshop 2, are shown in bold. Many risk cascades are highly interconnected, and therefore we also include theme maps that allow participants to explore the relationships between the different risk cascades. These theme maps are titled: electric vehicles, climate change, resource pressure, novel pollutants and work patterns (Table 1).

Table 1, *Output directory with hyperlinks to risk cascades, narratives and overview theme maps for the air quality case study. The four risk cascades prioritised as having high likelihood and impact, examined in workshop 2, are shown in bold.*

	Risk cascade	Theme
1	Weight (map; narrative)	Electric Vehicles (map) 
2	Perception (map; narratives)	
3	Scavenging (map; narrative)	
4	**Uptake (map; narrative)**	

<table>
<tr><td>5</td><td>Temperature Effects
(map; narrative)</td><td rowspan="3">Climate Change (map)
</td></tr>
<tr><td>6</td><td>Extreme Weather
(map; narrative)</td></tr>
<tr><td>7</td><td>Net-Zero Pressure
(map; narrative)</td></tr>
<tr><td>8</td><td>Financial Pressure
(map; narrative)</td><td rowspan="3">Resource Pressure (map)
</td></tr>
<tr><td>9</td><td>Government Resources
(map; narrative)</td></tr>
<tr><td>10</td><td>NHS Pressure
(map; narrative)</td></tr>
<tr><td>11</td><td>Novel Pollutants
(map; narrative)</td><td>Novel Pollutants (map)
</td></tr>
</table>

12	**Domestic Emissions (map; narrative)**	Work Patterns (map) 
13	Delivery Vehicles (map; narrative)	
14	Domestic Energy (map; narrative)	
15	Pollution Resilience (map; narrative)	

Biosecurity

The participatory process resulted in 14 individual risk cascades, which also have accompanying narrative versions (Table 2). The four individual risk cascades prioritised as having high likelihood and impact and that were examined in most detail are shown in bold. The individual Biosecurity risk cascades are highly interconnected, so in workshop 1 we used an overview map (Figure 9) and smaller themed overview maps (Table 2) to allow participants to explore the relationships between the different risk cascades. These theme maps are titled: dormant pathogens, accidental or deliberate release of disease, human-wildlife-livestock interface and post-outbreak scenarios.

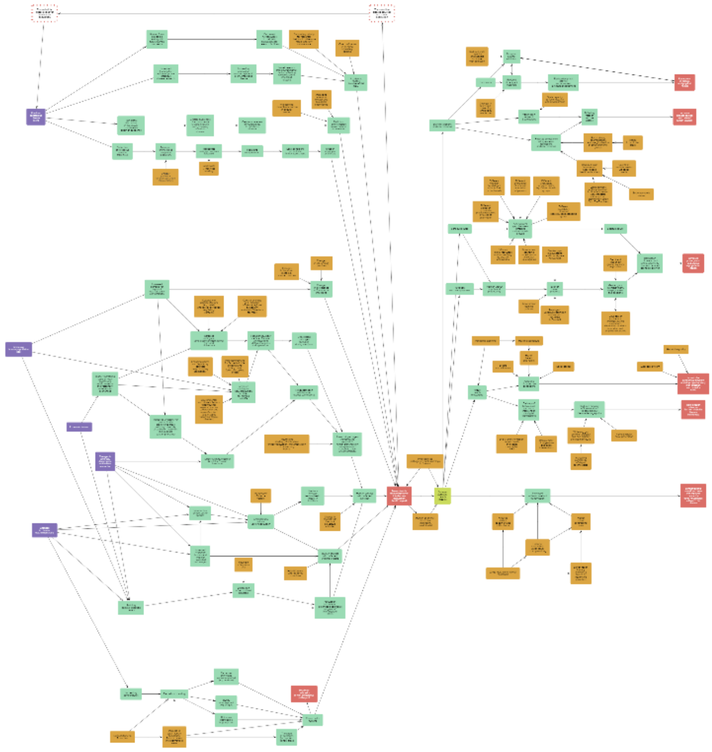
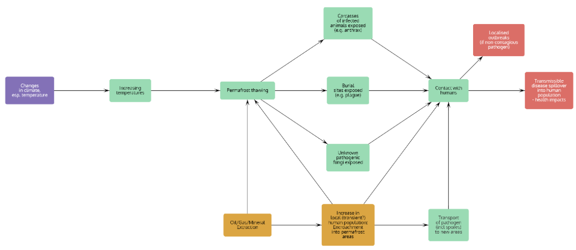


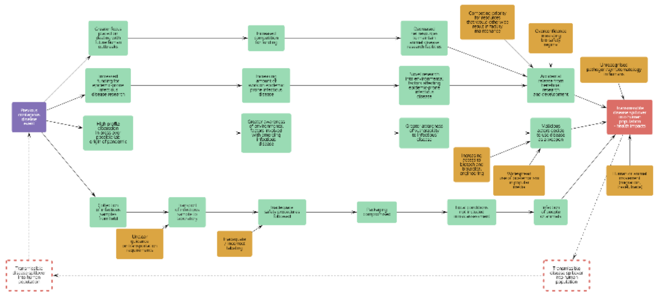
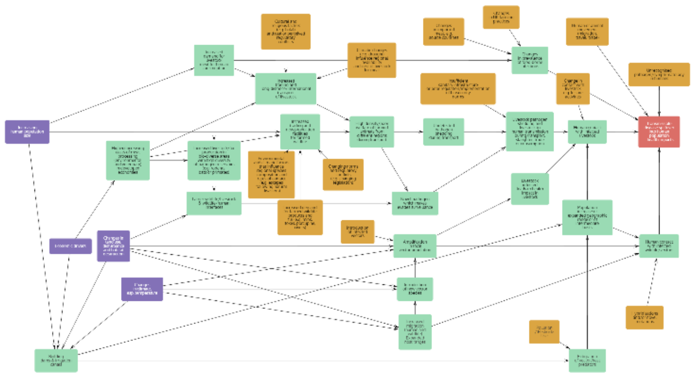
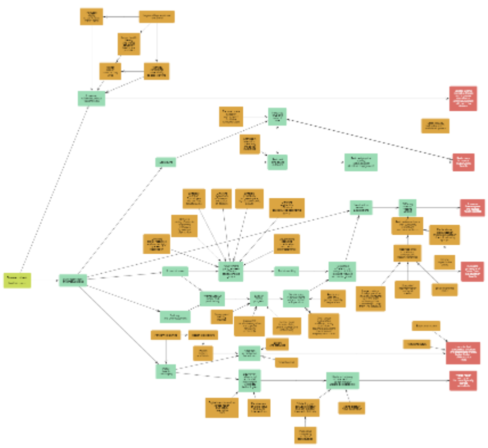
Figure 9, *Image of biosecurity case study overview map of the compiled risk cascades used in workshop 1. Primary drivers are shown in purple boxes, risk factors are shown in green boxes, threat multipliers are shown in orange boxes, and health impacts on UK populations are shown in the red boxes. Cascades were adjusted as the workshops continued. The full version in PRSM software can be found here.*

Table 2, *Output directory with hyperlinks to risk cascades, narratives and overview theme maps for the biosecurity case study. The four risk cascades prioritised as having high likelihood and impact, examined in workshop 2, are shown in bold.*

<table>
<tr><th></th><th>Cascade</th><th>Theme</th></tr>
<tr><td>1</td><td>Dormant Pathogen (map; narrative)</td><td>Dormant Pathogen (map)



</td></tr>
</table>

2	Resource Prioritisation (map; narrative)	Accidental or Deliberate Release (map) 
3	Novel Research (map; narrative)	
4	**Malicious Actors (map; narrative)**	
5	Sample Transport (map; narrative)	
6	Food-borne Pathogens (map; narrative)	Human/Wildlife/Livestock Interface (map) 
7	**Livestock (map; narrative)**	
8	**Wildlife (map; narrative)**	
9	**Household Transmission (map; narrative)**	Post Outbreak Scenarios 
10	Physical and Mental Health (map; narrative)	
11	Vaccine Uptake (map; narrative)	
12	School Closures (map; narrative)	
13	Gender Gaps (map; narrative)	
14	Public Health Messaging (map; narrative)	

Food Security

The participatory process resulted in ten individual risk cascades, which also have accompanying narrative versions (Table 3). The four individual risk cascades prioritised as having high likelihood and impact and that were examined in most detail are shown in bold. The individual food security risk cascades are highly interconnected, so in workshop 1 we used an overview map to help navigate these linkages (Figure 10). We also included three smaller themed overview maps (Table 3) to allow participants to explore the relationships between the different risk cascades. These theme maps are: environment and production factors, trade and economic factors and pandemic-related risk cascades.

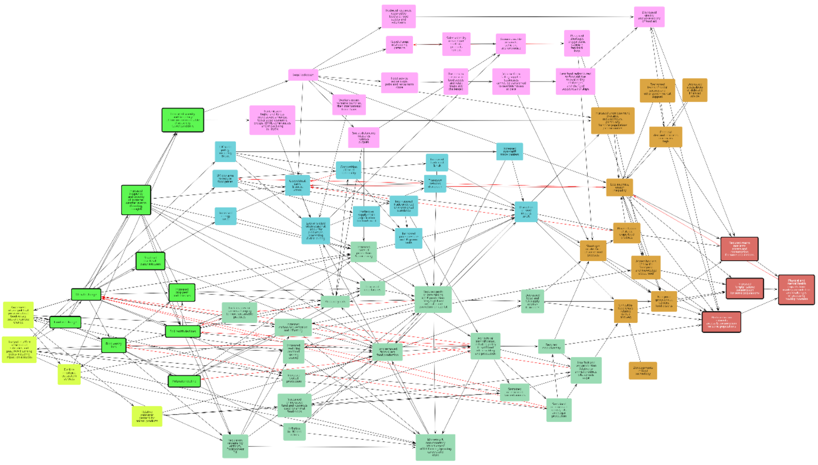
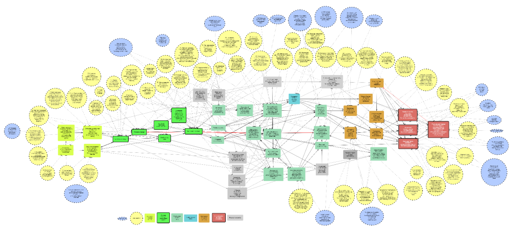
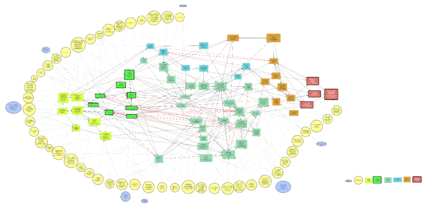
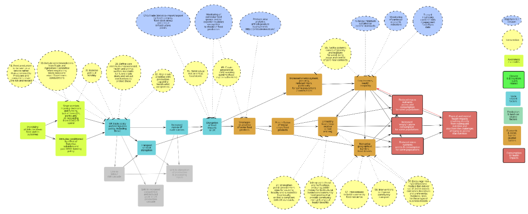
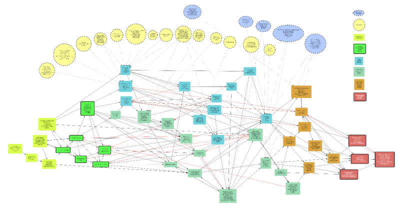
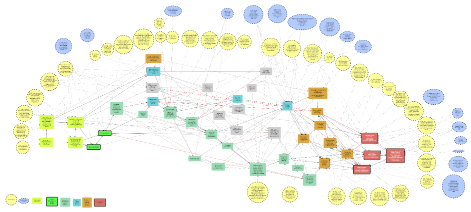
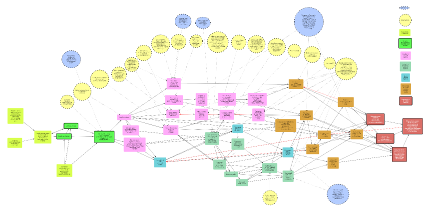
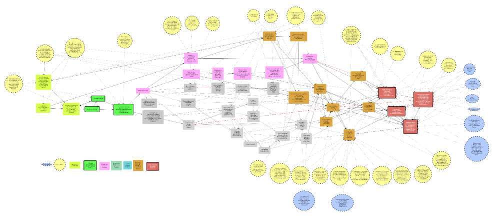


Figure 10, *Overview map of the compiled risk cascades used in workshop 1. Risk factors (boxes) are colour coded into broad categories of underlying attitudes (yellow), climate change related factors (bright green), production and land use factors (green), trade (blue), system shocks from disease related factors (pink) and economic and social barriers to equitable access to nutritious food (orange). Health impacts on UK populations are in the red boxes. Black lines show the risk cascades and red lines some of the main feedback loops. Individual risk cascades and links between them were adjusted as the workshops continued. The full version in PRSM software can be found here.*

Table 3, *Output directory with hyperlinks to risk cascades, narratives and overview theme maps for the food security case study. The four risk cascades prioritised as having high likelihood and impact, examined in workshop 2, are shown in bold.*

	Cascade	**Theme**
1	**Soil Health Decline (map; narrative)** 	Attitudes, Production and Land Use Risk Factors (map) 
2	Water Risks (shortages and floods) (map; narrative)	
3	Crop Pests and Diseases (map; narrative)	
4	Policy and Economic Impacts on UK Land Use (map; narrative)	

<table>
<tr>
<td>5</td>
<td>Non-tariff Trade Barriers
(map; narrative)
</td>
<td rowspan="3">Trade and Economic Related Risk Factors (map)
</td>
</tr>
<tr>
<td>6</td>
<td>Labour Shortages
(map; narrative)
</td>
</tr>
<tr>
<td>7</td>
<td>Trade Deals and Retailer-Grower Power Relationships
(map; narrative)</td>
</tr>
<tr>
<td>8</td>
<td>Human Transmissible Disease
(map; narrative)</td>
<td rowspan="2">Pandemic-Related Risk Factors (map)
</td>
</tr>
<tr>
<td>9</td>
<td>Impact of System Shocks (Such as the Pandemic) Given Increased Reliance on Food Aid
(map; narrative)
</td>
</tr>
<tr>
<td>10</td>
<td>Livestock Disease with Human Health Impacts
(map; narrative)</td>
<td></td>
</tr>
</table>

Reflections on the protocol

Participant selection

We sought to maximise cognitive diversity of participants in this project through a stratified selection procedure. In combination with the broad background of the SysRisk project team, this enabled participants with a breadth of systemic knowledge to work with those with a depth of expertise in particular areas, and allowed the cross-fertilisation of ideas and practices from other disciplines. However, there were some limitations and lessons learned from our approach, which we reflect upon below.

To ensure a wide range of expertise was represented during the workshops we selected participants and key stakeholders from the different spheres of the PESTLE framework (Political, Economic, Social, Technological, Legal/regulatory, and Environmental). Figures 11, 12 & 13 show the results of the scoring process, where participants were allocated percentages across the six PESTLE categories by SysRisk team members based on review of their research profiles and staff web pages. Participants were also asked to score themselves using the same system. This scoring process is further explained in the Appendix.

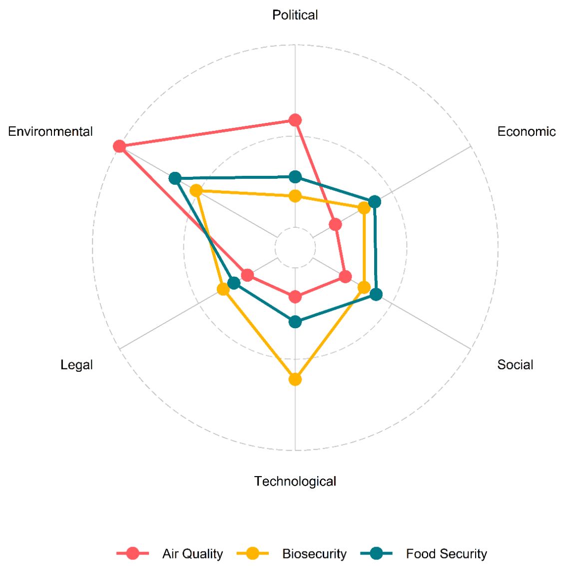


Figure 11, *Summary of assessment carried out by SysRisk team members of the participants' expertise according to 'PESTLE' categories for the three case studies.*

As evident in Figure 11, there was some expertise in all categories, reflecting the value in a systematic, stratified selection of participants. Note, however, that expertise was not always equally distributed across each category. For example, the air quality case study was strongly represented by environmental and political expertise but less on technological, social, economic and legal aspects. As part of the exploration of different protocols, we also asked participants to self-score their expertise. As shown for the air quality case study (Figure 12), there are some overlaps with assessments by the SysRisk team, but not perfect matching. For example, the SysRisk team appeared to overestimate political expertise compared with the participant self assessment. On reflection, self assessment by the participants is probably a more accurate reflection of expertise, but necessarily involves a longer lead time for the self assessment process before full involvement in the risk mapping process. In order to screen which participants to approach initially, a two stage process of external assessment of expertise followed by participant self scoring may be worthwhile.

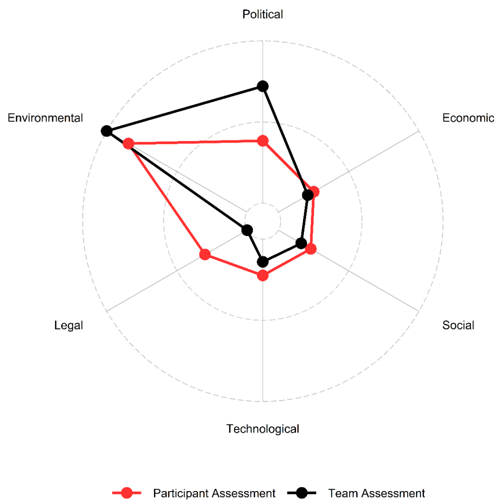


Figure 12, *For the air quality study, comparison of the assessment carried out by SysRisk team members of the participants' expertise according to 'PESTLE' categories versus self-assessment by participants. Only individuals with both team and self assessment scores are included (n = 9 participants).*

An additional limitation with our approach is that there may be elements of expertise not well reflected in these PESTLE categories, e.g. in risk management. This expertise is obviously important for formal risk assessment processes (e.g. in government and policy making), which seek to further develop the risk appraisal approaches taken here.

We did undertake some further categorisation for selecting participants in the food security and air quality case studies. As an addition to selecting participants from PESTLE analysis alone, potential air quality case study participants were considered in terms of their health expertise. Potential food security case study participants were recruited additionally considering their expertise across six food system activity areas: producing, processing, distribution, retailing, consuming and recycling (Hasnain et al., 2020). The relative expertise of each of the food security participants across each of the six activities was determined by percentage allocation in the same way as the original PESTLE allocations (Figure 13).

Figure 13, *For the food security case study, summary of assessment carried out by SysRisk team members of the participants' expertise according to six food system activity areas.*

Considering this additional selection criteria for participants of the food system case study (Figure 13), we might ask what are the equivalent air quality and biosecurity activity systems, and would defining these at the beginning of the process have changed our project outputs? We note, as an example, our selection of participants for air quality across may have been different if we also attempted to stratify selection across various systems that contribute to air quality emissions, such as energy, transport, industry, and health. It may be that, as a result, interventions identified and risk cascades produced from the workshops would have been broader.

Another way to achieve broader perspectives may have been to select different participants for each part of the process (workshops 1, 2, & 3), in order to prevent issues surrounding siloed thinking, where participants, mostly unintendedly, focus narrowly on their area of expertise. In air quality research, for example, there is a frequently raised concern that academics consider problematic issues, but are less focussed on solutions-oriented thinking, which often sits with specific industries and other actors. Whilst a wide-range of academic and non-academic experts were invited for risk cascade identification (workshop 1), in the subsequent identification of interventions (workshop 2) it may have been beneficial to invite specific experts relevant to key sectors involved in the risk cascades. Attempting to identify these actors or industries for workshop 2 at the outset of the project would have been difficult, as broad expertise was required for the initial risk cascade identification; therefore, a second-round of participant selection would be required.

A further consideration in maximising cognitive diversity may be selecting participants to ensure balance of gender, career stage, and even including those who are not academic experts but, instead, representatives of communities commonly affected by risks. Whilst we considered such issues in the process development phase, we were limited by participant numbers and therefore decided to focus our stratification of experts on a smaller number of factors, though we did try to achieve gender balance as much as possible through our initial scoping of experts.

Participant familiarity with the themes of the project was a further limitation encountered. It was observed in all case studies, but particularly for air quality and biosecurity, that participants sometimes seemed either reluctant or doubtful of their abilities to comment on points that strayed from their area of expertise. This was predominantly observed when participants were asked to score interventions from the other case studies based on their multifunctionality. Interestingly, some participants were also reluctant to comment on the degree of current implementation of interventions from their own case study. In the air quality space, participants are perhaps more used to thinking about a particular part of the system (namely, emissions of pollutants) rather than the underlying systems that cause them, and so this potentially limited the air quality participants' ability to access and discuss a broader set of cascades and interventions. Conversely, food security participants tended to be more familiarised with interdisciplinary interactions and crossing disciplinary boundaries (e.g. individuals working with food systems already come from marketing, health, or business backgrounds), which aided them in commenting on and discussing broader topics. Participants from the food security case study were arguably more used to the concept of systems thinking and analysis, and discussed this in what could be described as their 'normal' ways of working. This perhaps enabled them to identify more interventions of a wider range, and to appreciate more quickly the underlying concepts of the project.

Uncertainty in systems thinking in the biosecurity case study may have been an explanation for several participant dropouts throughout the project. As an additional exacerbating factor, biosecurity participants were not already engaged in communities which often work together, as seen for food security (five participants withdrew from the participatory process and had to be replaced, compared with one for food security and one for air quality). Additionally, familiarity with the project team and pre-existing relationship with them likely played a role in the investment of the food security participants to the project. In the air quality and biosecurity case studies only a few of the participants had previously worked together and had no previous contact with any members of the SysRisk team. This may be less of an issue for government-led risk assessment processes with greater convening power.

Defining boundaries in systemic risk analysis

As described by Cash *et al.* (2006), taking into account different types of scales and cross-scale interactions leads to more successful assessment of problems and solutions that are politically and ecologically more sustainable - a multilevel world requires multilevel solutions. The spatial, temporal, and jurisdictional boundary scales, summarised and presented in Figure 1 of Cash et al. (2006), have been used to structure our reflections on boundary choices in this project.

Spatial Boundaries

The focus of our project was on the appraisal of risks to the health of UK citizens, even though those risks may play out across international systems. The backgrounds of participants and their perspectives both on how risks play out and how interventions need to be implemented across the spatial scale, likely differ from those of policy makers, and each other. For example, participants' underlying worldviews influence the different definitions of food security that they hold, which also relates to how they view spatial scale, e.g. food security is sometimes equated with UK self-sufficiency (Barling et al., 2008) or the maintenance of the status of food supplies to the UK, rather than a more universal definition we have used in this SysRisk project of accessibility to sustainable and healthy food. Additionally, we found that participants were keen to discuss current or salient risks, e.g. the labour shortage and its effects on food security, or housing insulation protests and their influence on policy and air quality. Although the project was funded under a UK Research Council call around Covid-19 impacts and UK recovery, risk factors typically ended up spanning outside that remit, with Covid-19 being simply a starting point that linked to discussions about deeper systemic concerns.

Although the aim of this project was to engage participants in thinking about UK risk reduction and resilience, many rightly proposed threats that are actually global ones. This different thinking about spatial scale is relevant for whether participants proposed local, national, or international interventions and implementation ideas. In the air quality space in particular, this is highly dependent on the spatial dynamics of the risk (e.g. indoor vs outdoor air quality). Novel pollutant interventions, which generally consider outdoor spaces, could potentially require international regulation if emitted pollutant species have long atmospheric lifetimes (long-range transport of air pollutants means species emitted abroad may affect the health of UK residents, and vice versa - WHO, 2021b). In contrast, some interventions related to working patterns (e.g. the domestic emissions risk cascade regarding home/workplace ventilation) that could be implemented locally by each of the four UK nations. This example shows how the spatial consideration of an intervention is dependent on the spatial nature of the risk.

Jurisdictional Boundaries

The SysRisk processes focused on UK national government risk mitigation strategies, but it is crucial to consider jurisdictional scale when considering legislative interventions. Adapting the process to do this is very much conditional on what type of intervention is being considered. Scaling of regulatory interventions may be problematic, as scaling down to a local (e.g. council) level may be more difficult as local authorities do not have the same enforcement power as at the national government level. Equally, there are difficulties scaling up regulatory interventions to the global level as this would usually be dependent on the cooperation and agreement of many nations, which in most cases is not straightforward or timely. On the other hand, education and mindset change interventions, such as stressing relevant hygiene measures to reduce disease transmission, could be rescaled to both local and global levels more easily as implementation is based in influencing public capability, opportunity and motivation (Michie et al., 2011) , which can be carried out in various ways without always requiring legislative change.

Temporal Boundaries

It is clearly important to specify temporal horizons in the assessment of risk. In this project, the boundaries for this project were limited given we were considering salient environmental risks as part of the national recovery to Covid-19. To raise the profile of environmental risk these case studies were selected as risks are likely to be realised over a period of just a few years. Nevertheless, we did factor in longer term processes that cause amplification of risk such as global land use degradation, climate change, geopolitical change and demographic change.

Understanding risk pathways on longer term timeframes is crucial if we are to build resilience. The most obvious example is around non-linearities (including 'tipping points').

Although certain risks may not be realised for some time in terms of a dramatic change in state, the erosion of resilience occurs prior to this. For this reason, there has been a call in some disciplines such as ecology to develop indicators of resilience (*cf.* 'early warning indicators') rather than simply monitoring system state (Quinlan et al., 2015; Burthe et al., 2015; Weise et al, 2020). For example, pollen delivery to crops is a measure of pollination state (which could theoretically decline relatively quickly), but pollination function resilience based on species richness and functional composition would give a better early warning signal (i.e. showing a more gradual decline which warns of impending crash in pollination function; Oliver et al., 2015).

In this project, our data/monitoring watchpoints may give some indicator of system resilience to non-linear changes, but more work is needed on understanding these changes and what to expect (Lenton et al., 2008). Hence, in addition to data watchpoints, the right models (both qualitative and quantitative) of potential system collapse dynamics are needed, which requires robust underpinning science.

An additional limitation is that the reductionist approach used in this project meant compounding risks were largely excluded. Although some factors such as land use degradation and climate change were included as exacerbating factors, it was unfeasible using this approach to exhaustively include all factors whose dynamics over time could result in systems becoming more susceptible to hazards. Therefore, it is important to recognise that our approach, although detailed, is certainly not exhaustive.

Environment-mediated risks

Participants were specifically asked to consider environment-mediated risks in this project. This meant that we specified that risk cascades should include at least one environmental factor, although they included other factors too (e.g. risks cascades were impacted by social, economic, political, technological, and legal factors). The narrowing of focus to specify risks as necessarily having to include environmental factors would not be sensible in a full scale application of the systemic risk appraisal process; in which case, it would be important to determine how to define the topic boundaries at the start. Considering environment-mediated risks led to a multiplicity of risk cascades and was a daunting challenge in itself. Removing this constraint could lead to the process becoming unwieldy and too partial in its exploration of risk. One approach would be to look at clusters of drivers such as those shown in Figure 1 (EEA, 2020b). In broadening the scope of the process however, it is essential to ensure that discussions remain multi-disciplinary and cross-sectoral.

Facilitation processes

The Covid-19 pandemic has necessitated the adoption of virtual meeting spaces across a range of industries. This project was no exception, with all meetings and workshops conducted remotely via online video platforms. Participatory exercises, typically carried out using whiteboards and Post-it notes (or other alternatives) were replaced with web applications such as PRSM and Mural. For the workshops, the use of virtual meeting spaces offered considerable advantages. For example, participants were not required to travel to attend workshops, meaning that regardless of where a participant was based there was no barrier to attendance based on distance. This meant that participants may have been more willing to join multiple, short workshops, throughout the year. Whilst there are clearly benefits to online working, there are also some negatives that need considering. First, online discussion may have been more stifled than in-person, due to the fact that online meetings and workshops are not the typical way of working and people are not yet fully comfortable with the patterns and etiquette of online discussions (although this is questionable considering the widespread adoption of online meetings over the past two years). Online discussions are also sometimes hampered by occasional poor internet connections rendering participant and facilitator contributions inaudible at times. Second, the use of online tools such as PRSM is open to more technical issues than simple in person exercises (e.g. using a whiteboard and Post-it notes). Although intuitively designed, more detailed explanations are required, software errors are possible and there is no way to guarantee that all participants are viewing the same things at the same time (e.g. carrying out the exercises on PC screens vs tablet screens). Dealing with these factors can result in considerable time lost from the workshops. In the SysRisk workshops, participants experiencing software problems were invited to leave the breakout room to discuss their issues with a member of the project team who would attempt to identify and resolve the issue. Participants then returned to their breakout room after the issue was resolved.

As described in the Participant Selection section of the report, a number of participants were unable to contribute to all aspects of the project. This required the addition of new participants to retain a balance across the PESTLE categories and keep manageable numbers in workshops. One impact that this had on the project was less informed discussion in some areas. For example, there were occasions where interventions were added in workshop 1 by a participant who subsequently left the project; then, in workshop 2, this intervention was removed by other participants. Had the initial proposer been present at the second workshop there may have been debate over its removal, with a potentially different outcome. This problem was not only due to participant drop outs, but also the structure and format of the workshops, as splitting participants into manageable breakout groups (of approximately 6 people) also meant there was less expertise covered per group. A possible solution to this issue would be that the breakout groups reviewed all four cascades in workshop two, rather than only two each. However, this would require longer workshops.

One aspect that was relevant to all case study workshops, but particularly workshop 2, was the willingness of participants to address specific aspects of the risk cascades and the implementation of interventions. Understandably, participants were more comfortable talking more generally about the issues, particularly when they fell outside of their area of expertise. Active facilitation was required by the project team to ensure discussions covered the required specific questions (see SysRisk process and project materials section above) and for the desired aims of the workshop to be met.

The framing of any analysis is important, and in this project it likely affected how participants identified interventions. One consideration is whether we gave enough focus on the need for systemic transformation to address risks (e.g. as recognised by many science-policy initiatives; EEA, 2020a). Under the 'three horizons' approach (Sharpe et al., 2016) this relates to horizon three thinking, where interventions aim to dramatically transform the system to a more desirable state (with less vulnerability or exposure to systemic risk). In contrast, other participants may focus horizon one interventions on, which tend to be more incremental improvements, in some cases supporting the maintenance of the status quo.

The final synthesis workshop of our project (workshop 3) was framed as a deep dive into the implementation of selected multifunctional interventions, assessing the enablers and barriers and winners and losers of these specific implementation approaches. The selection of multi-functioning interventions was done by each case study team, using a semi-quantitative approach whereby team members discussed each intervention and came to an agreed decision on whether interventions from the other case studies had any impact on their own. This method provided interventions that the project team deemed highly multifunctional, but it is possible that participants may have disagreed with the project team's scores. When asked to score the multifunctionality of interventions after the final workshop, participants were understandably reluctant to score aspects they deemed outside of their expertise. This may have also contributed to the low number of scores returned by participants after the workshop.

Watchpoints

The participatory process involved the identification of watchpoints defined as datasets of monitoring initiatives that help identify if a certain risk is becoming realised, i.e. an indicator that the socio-environmental system is changing in such a way that makes that type of risk more likely. These can be found in the risk cascades and narratives in the Project Output directory. One constraint was that limited time available and breadth of expertise across the participants led the SysRisk team to feel that this process was not exhaustive enough. In retrospect, more time devoted specifically to watchpoints (for example, a specific workshop rather than combining with the activity to identify interventions) would have been better. Furthermore, it was recognised that some important watchpoints may only be known in closed circles (e.g. national security risk assessments conducted by government). In principle, bringing in a broader set of experts and providing more time devoted to this activity would help to produce a more exhaustive set. This could be valuable for initiatives aiming to track risk in real time (e.g. the UK government Cabinet Office 'Situation Centre'). In principle, these watchpoints enable early warning of non-linear changes (Lenton et al., 2008) and rapid propagation of systemic risks. However, they would benefit from careful consideration, involving incorporating into theoretical and empirical models of system resilience, in order to be most useful.

Types of interventions

Three key points for reflection emerged from discussion about the range of types of interventions: i) whether interventions are proactive or reactive, ii) whether they address mainly shallow or deep leverage points, and iii) whether they are specific to that case study or provide multifunctional co-benefits to the other case studies. These aspects relate to various strategies for enhancing resilience: robustness (maintain status quo), recovery (bounce back) and reorientation (transform) (GFS FSR, 2021). From the point of view of reducing systemic risks, some aspects of system robustness and recovery can be undesirable (Oliver et al., 2018). This is because they 'lock in' aspects of the system that might appear to deliver benefits (e.g. cheap food in the short term) (Benton & Bailey 2019), but that maintain vulnerability to systemic risks (e.g. increasing food insecurity in the longer term through degradation of ecosystem services, such as soil health, pest control and pollination, on which agriculture depends; Mbow et al., 2019). In the food security case study, we found discussion about interventions was often focused on those aimed at a reorientation strategy (see 'horizon three' thinking referenced above; Sharpe et al., 2016). Participants were often proposing to address systemic risks through proactive interventions aimed at systemic transformation. In contrast, interventions raised in the air quality and biosecurity case studies tended to be focussed on increasing the robustness of the existing system, or framed under an implicit narrative of bouncing back from Covid-19.

Reactive *versus* proactive interventions

Interventions can be placed on a scale from purely reactive interventions to highly proactive interventions. Reactive interventions are those put in place to mitigate or adapt to an existing or developing risk, perhaps in response to information from a data/monitoring watchpoint. Proactive interventions are those put in place in anticipation of future risks and include a larger role for prevention. For example, many interventions in the air quality case study were proactive, involving research and regulatory interventions to improve monitoring capacity and to predict and prevent emerging risks such as novel pollutants. Across the case studies, there was a mix of reactive and proactive interventions (e.g. Table 4), but arguably a greater overall focus on proactive interventions perhaps because several of the pathways through which systemic risk could materialise (the 'risk cascades') were still hypothetical.

Table 4, *Examples of reactive and proactive interventions from the three case studies.*

	Reactive	Proactive
Air quality	Combined approaches (ventilation, air purifying and facemasks) to tackle Covid-19 to alleviate the increased amount of energy required to heat homes when ventilation alone is used.	Make horizon scanning/risk models for novel substances mandatory before manufacturing of products containing new chemicals is permitted.
Biosecurity	Develop improved therapeutics to reduce the impact of disease (reactive if in response to specific, known disease threat e.g. covid therapeutics).	Targeted surveillance of livestock for known zoonotic pathogens to increase the likelihood of catching disease outbreaks before they spread further.
Food security	Introduce food rationing as a response to system shocks.	Shift attitudes from food consumers to food citizens and incorporate a right to accessible nutritious food into policy making.

Deep *versus* shallow intervention points

In addition to a preference for proactive interventions, participants emphasised interventions that aim to create systemic change and disrupt the risk cascades, rather than adapt to or mitigate individual factors on the cascades. Donella Meadows (1999), a seminal researcher in systems thinking, described 12 points in which to intervene in a system, ranging from shallow leverage points such as subsidies, taxes and standards, to deep leverage points such as 'changing the rules of the game', changing people's mindsets and new paradigms. With increasing depth comes increasing ability to create system wide change. Abson et al., (2017) aggregated these 12 points into four system characteristics: 'Parameters' are the modifiable, mechanistic characteristics of the system such as taxes, incentives and standards, or the stocks and rates of flow of physical elements of a system, such as pollutants, animals and food products. 'Feedbacks' include interactions that drive or that provide information about desired outcomes. 'Design' includes the social structures and institutions that manage feedbacks and parameters.

'Intent' includes the underlying values, worldviews and goals of the actors that shape the emergent direction to which a system is oriented (Figure 14). Considering the implementation of interventions through this lens can help demonstrate barriers to systemic change.

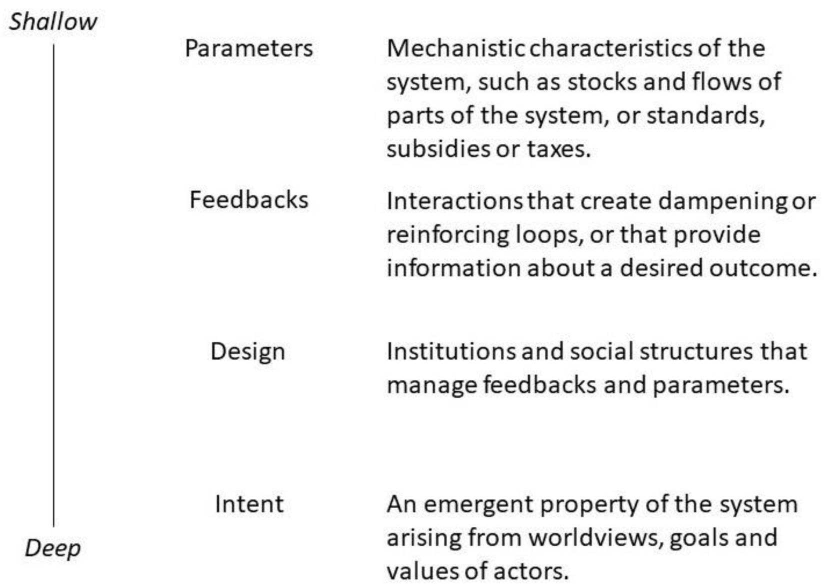


Figure 14, *System characteristics at different depths as categorised by Abson et al. (2017), based on leverage points described by Meadows (1999). Adapted from Abson et al. (2017).*

Rather than the interventions identified in this project inherently targeting 'deep' or 'shallow' system characteristics, the majority involved actions that influenced the system at multiple depths. For example, an air security intervention to improve walking routes (Table 5), occurs at the parameter level because it alters the movement of people and vehicles, resulting in a change in the amount-, distribution of- and exposure to- air pollutants. However, implementing this requires change in institutions and social structures, with feedback loops operating to potentially reinforce this change, for example providing knowledge and capacity to alter transport policy.

In this way, deeper system characteristics constrain what is possible at shallower system characteristics (Abson et al., 2017). For example, the success of improving tracking of livestock provenance and associated biosecurity standards at a parameter level is likely dependent on underlying values and institutional capacity (Table 5). A certain amount of change at the 'intent' level is needed in order to implement change within standards or properties of the system. However, change in these underlying values and mindsets is then also further enabled by capacity building in institutions and by the creation of feedback loops (Markus & Kitayama, 2010).

In most cases, interventions need to be implemented at multiple depths, or along with other complementary interventions, in order to be effective (Oliver et al. 2018; OECD, 2021). For example, providing food labelling information alone will have limited impact if this is not perceived to involve accurate information from trusted institutions (Table 5) and if it is not part of a suite of wider complementary interventions that enable behaviour change. A systems approach can encourage coordination between different policy communities to design policy frameworks with interventions across the system (Institute for Government, 2011; OECD 2021).

Many of the interventions identified in this project had a strong focus on awareness raising, which reflects participants' eagerness for interventions that leverage change on deeper system characteristics to result in transformational change (e.g. Table 5). This is also reflected in some global food system initiatives such as the Conscious Food Systems Alliance being developed by the UN Development Programme. However, it is important to note that awareness raising is only one element, with capacity, opportunity and motivation also required for translation into action (Michie et al., 2011). This highlights the need for complementary interventions that target multiple elements of the system and risk cascades. There can be a danger in emphasising awareness and educational interventions alone while maintaining an existing institutional framework that strongly constrains physical, economic and social accessibility and acceptability and therefore maintains the status quo. Hence, conceptual models which consider complementary interventions comprising a mix of individual, social and material factors, such as the 'ISM' model developed by Darnton & Horne for the Scottish Government may be valuable (Darnton & Horne, 2013).

A major barrier repeatedly raised by participants within the food case study was that interventions aiming to alter incentives and structures to create a more sustainable, more resilient and more equitable system can sometimes seem politically unacceptable. This applies both to interventions targeting supply side processes (where producers and retailers can be locked into particular practices) and demand processes (where consumer 'choice' is influenced by multiple conditions and constraints; Mbow et al., 2019). Some participants reflected on an apparent unwillingness to be seen as dictating dietary choices; for example, around the National Food Strategy proposal to tax sugar and salt (Dimbleby 2021; Vaughan 2021), and the relatively limited public, policy and industry commitment to the importance of dietary shifts in reducing climate change and improving health (Food and Drink Federation 2021; Swinburn et al., 2019; Poore & Nemecek 2018; Committee on Climate Change 2020). This reveals underlying societal differences in aims and definitions of food security at the 'intent' level. Our participants tended to emphasise the reorientation aspect of resilience, with food security defined as equitable access to healthy, sustainable food (Doherty et al.,2019). However, UK food security is often aligned with robustness and recovery strategies of resilience with the maintenance of supply of the current range of products (Lang & Barling 2012; Oliver et al, 2018).

Table 5, *Example interventions from the three case studies, showing how implementation of interventions can occur at different levels, as categorised by Abson et al., (2017). See main text for definitions of these levels.*

Intervention	Parameters	Feedback	Design	Intent
Air quality - Improve walking routes, including safety (& perception of safety)	Aims to change the pattern of movement of people and vehicles and therefore the amount, distribution and exposure to air pollutants.	More people using these routes creates positive feedback. Information from people using or not using these routes further tailors implementation and influences design.	Requires increased collaboration between various institutions and social structures and potentially the formation of new groups, e.g. between local government, community groups & researchers.	Requires buy in from multiple stakeholders in order to motivate action.
Biosecurity - Improve tracking of livestock provenance and associated biosecurity standards, in order to reduce risk of disease spread during livestock transport.	Requires altered standards and agreements that might alter the quantity and pattern of movement of animals.	Increased sharing of information between different parts of the system.	Requires the development of new working groups, regulatory bodies and the strengthening of relationships in order to manage change.	Requires the development of a shared understanding about aims and a willingness to bear associated costs.
Food security - accredited and transparent environmental food labels	Mechanistic change might be required for implementation, such as new regulations and industry standards.	Potential for a stronger feedback loop if this modifies consumer demand.	The need to collect and share information could drive stronger relationships between organisations and modify power relationships.	Increased awareness of the impact of dietary choices and different production practices. Increased transparency both drives and requires change in values and mindsets.

Multifunctional *versus* specific interventions

Multifunctionality of interventions, in the scope of this report, was defined as the ability of an intervention to simultaneously impact the other case studies, either as a co-benefit or a trade-off (Table 6). In many cases, co-benefits extend beyond our case studies. For instance, synergistic interventions addressing biosecurity, air quality, and food security can also be beneficial for reducing emissions of greenhouse gases to help tackle climate change. Nature-based interventions improving food security and biosecurity (e.g. low intensity agroforestry) provide multiple additional functions such as biomass production, carbon storage, flood regulation and biodiversity conservation (Manning, 2018). In addition, the identification of potential trade-offs amongst interventions can help to reveal lock-in effects where progress in one of the case studies may limit progress in others (Pradhan, 2017).

We found that the biosecurity case study exhibited the most co-beneficial interventions compared with other case studies: 34 of the 49 (70%) interventions in the biosecurity case study were deemed to be co-beneficial to food security, although only nine (18%) were deemed beneficial for air quality (Table A3). Food security interventions were also often beneficial in terms of reducing risks in the other case studies: out of the 69 interventions for food security, 16 (23%) were synergistic with biosecurity and 19 (27%) with air quality. In contrast, interventions in air quality case study generally showed fewer interactions with other case studies: 37 of out of a total of 44 interventions (84%) indicated limited effect or were context dependent in relation to biosecurity, and 34 (78%) in relation to food security. Across all case studies, there were very few clear trade-offs in terms of an intervention in one case study increasing risk for another (Table A3), but there were a relatively large number of context dependent outcomes.

Table 6, *Example of interventions deemed to be multifunctional in terms of reducing multiple types of risk (across the case studies) versus those with specific, limited benefits to only one case study.*

Case study	Multifunctional intervention example	Case-study specific intervention example
Air quality	Address tensions between insulation and ventilation (insulation supports energy efficiency, while ventilation helps with indoor air pollution, exposure to Covid-19) to improve both personal exposure to indoor pollutants and decrease domestic emissions from heating/cooling *[enhances biosecurity]*	Increase in consistent and universal charging point network to encourage the electrification of fleet of cars/vans by 2035 and decrease the persistent use of existing fleet beyond that point
Biosecurity	Support and encourage behavioural changes to reduce demand for animal products *[enhances food security]*	Improve detection and response capabilities for the misuse of biotech to reduce the ability of individuals to attain and use bio-weapons. Create a deterrent by denial effect.
Food security	Create new narratives around food and campaign to shift to healthier diets with lower environmental impacts *[enhances biosecurity through reduced land use degradation and healthier populations]*	Increase investment in UK horticultural innovation (particularly social-innovation) and training.

One of our findings was that multifunctional interventions tended to be described in more vague terms, i.e. they were less specific in terms of ownership and the allocation of resources for successful implementation. Therefore, we conducted an additional participatory workshop (workshop 3) to break them down further to produce more tangible implementation strategies. An illustration of this is shown in Figure 15 for the biosecurity case study. In this exercise, the participants (grouped by case study) reflected on the barriers and enablers for the execution of interventions and identified key actors responsible for such actions, along with potential winners and losers and potential negative outcomes from the implementation of interventions. For example, for the biosecurity intervention 'Support and encourage behavioural changes to reduce demand for animal products', one possible implementation would be to 'Subsidise the cost of healthy vegetarian and vegan products' (Figure 15). This would be implemented by actors including government, employers that have staff canteens, and higher education establishments. Potential negative outcomes could lead to increased budget constraints, possible health impacts due to less vitamins and minerals in vegan alternatives (which can be mitigated, importantly, with culinary and dietary training). The implementation of this strategy identified more environmentally sustainable plant-based agriculture as a potential winner, whilst potential losers were suggested to be livestock producers.

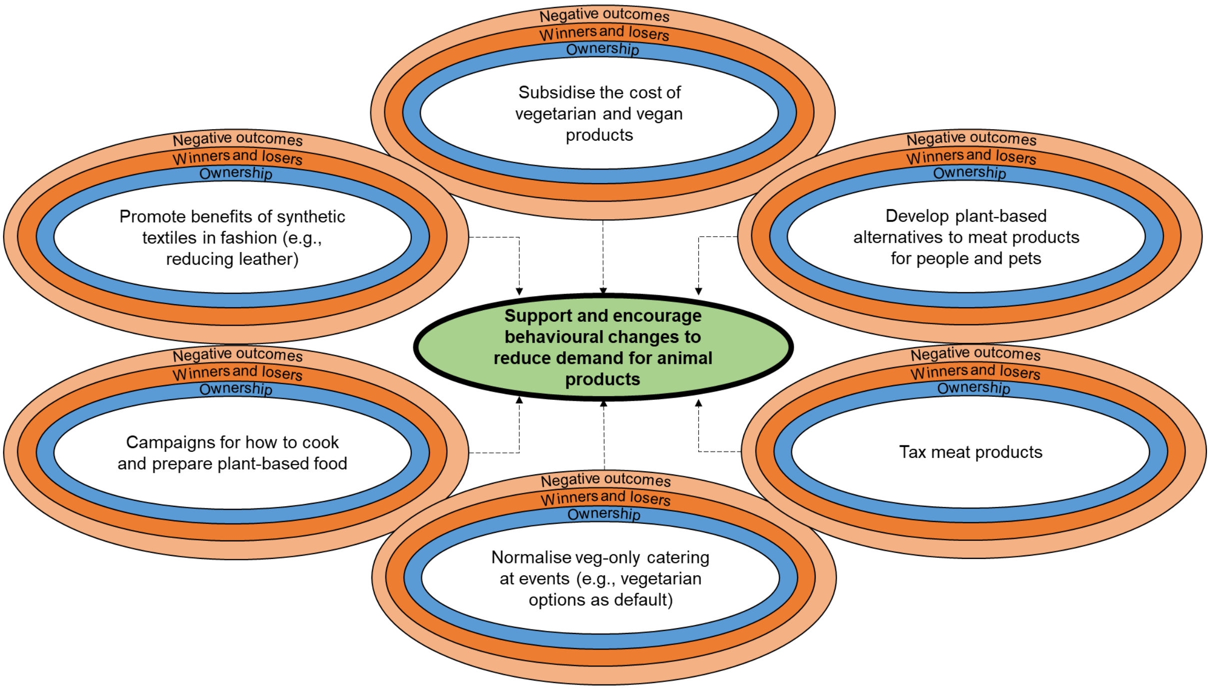


Figure 15, *Example of different ways that a multifunctional intervention from the biosecurity case study could be implemented.*

Conclusion: the way forward for systemic risk analysis and governance

This project has explored a methodology to appraise systemic risks for three case studies, including the identification of 'watchpoints' to track risk and potential interventions to reduce risk. We identified a number of limitations and caveats detailed throughout this report, and these are further considered in terms of future recommendations below. Notwithstanding such refinements and additions to the method we undertook, the lessons learned from the project lead to the following overall recommendation:

To deal with systemic environmental risk, we recommend a participatory systems mapping approach with inputs from diverse experts to identify interventions, then a follow up process using a systems approach to understand key considerations of the interventions to assist with their prioritisation.

This aligns with the the following more detailed recommendations:

Participant selection

Recruiting experts in a stratified way to enhance cognitive diversity. For example, this can be done firstly to cover PESTLE categories (i.e. political, economic, social, technological, legal/regulatory or environmental), thus enabling an overall broad systems approach (Figure 5). This may then be supplemented with additional stratification, e.g. by sector and 'activity-system' as was done for our food system analysis. Further considerations could be to include targeted specific expertise in areas such as risk management and health.

Online workshops

Running workshops online using interactive software such as PRSM used in this project. Online workshops enable a wider range of experts to be involved in the project by demanding less of their time and also reducing the environmental costs of travel. The trade-off with this approach is that shorter online meetings need more careful facilitation to ensure they deliver everything required. Also, careful time and planning is needed to ensure any software is understood by all and works effectively.

Participatory systems mapping

Using participatory systems mapping to ensure that key pathways by which risks propagate through socio-environmental systems are not neglected. There is a tendency of some to jump to quantitative approaches to model aspects of systems they know well or for which data are available. But it is probably better to know more approximately about the most important elements in a system than to know a small part in great detail and ignore the rest (Vester, 2007). This requires approaches involving the participation of broad expertise. As economists John Kay and Mervyn King suggest in their book *Radical Uncertainty* (Kay & King, 2020) "Good decisions stem from using non-quantitative information combined with experience and learning from others". Approaches such as Bayesian belief networks, system dynamics models and digital twins were all discussed by the project team, but were considered to be more appropriate as secondary steps compared with an initial more holistic conceptual approach using participatory systems mapping. However, we were also limited by time in this project and, in retrospect, longer to develop the risk cascades, identify key factors and linkages to other risk pathways, would have been valuable. Therefore, we see these risk cascades as 'living documents' to initiate conversation with different actors down the chain about what data exists, what data could exist and how effective watchpoints could be developed. These further conversations should add additional perspectives and bring new insights that can then be added to the risk cascades and narratives.

Prior work to set the boundaries for analysis before developing risk cascades. In this project it was important to clarify that we were interested in risks to the health of UK citizens, but that risks could cascade internationally, and certainly do not only involve only environmental factors (i.e. we worked on 'environment-mediated' risks but did not limit ourselves to only considering the environmental sphere).

Futures approaches

Using explicit futures methods to overcome cognitive biases. Understanding how risks may play out is challenging, and susceptible to cognitive biases such as availability bias (i.e. focussing on salient patterns and events that happened recently). Furthermore, because interventions are likely to take time to put in place and should mitigate against future risks, there is a need to consider how socio-environmental system dynamics may be changing, i.e. interventions developed with status quo conditions in mind may be less fit for purpose in the future. Therefore, it is important to encourage participants to consider how conditions may change in the future, e.g. with climate change, geopolitical shifts, economic change etc. It can be challenging to do this implicitly and more explicit Futures methods, such as scenarios, may be valuable to ensure that different plausible futures are appropriately explored.

Identifying system 'watchpoints' to build effective monitoring capacity. This is in order to assess whether socio-environmental systems are changing in ways that make certain risk cascades more likely to be realised. This project identified a number of watchpoints including datasets and monitoring schemes. Ensuring broad expertise and sufficient time to identify these is essential.

Dealing with uncertainty appropriately

Complementing risk appraisal with general resilience building. Although the participatory systems mapping approach with broad expert input that we advocate allows a more holistic appraisal of risk, it is still inevitably reductionist in terms of focusing on specific risk cascades and interventions. The approach is more comprehensive than risk assessments developed from sector-specific siloes, though it will never, of course, be fully comprehensive. Complex systems, by definition, change in ways that we cannot always anticipate. Therefore, there is a need to complement this type of risk appraisal with more general resilience building approaches. In practice, some of the interventions identified through this participatory systems mapping address key drivers and this also tends to promote general resilience. For example, reducing poverty, tackling unsustainable consumption and building population health are all 'multifunctional' interventions that address specific risks, as well as building resilience to unknown threats.

Refining interventions

Combining with additional systems approaches to help prioritise interventions. The process outlined in this report helps to take a broader lens to identify interventions across different sectors and move beyond solely reactive responses to risk (i.e. 'sticking-plaster' interventions aimed at proximate symptoms), and towards addressing deeper drivers of change. This inevitably produces a large number of possible interventions. Policy teams often have strong expertise in some elements of prioritisation, such as considering the cost, feasibility and deliverability of interventions. Additional elements that need to be considered include equity issues (e.g. losers/winners), trade-offs and co-benefits ('multifunctionality') of interventions. Our project found that certain interventions are relatively neglected, even though they would address multiple types of risk. This is perhaps inevitable given the siloed nature of government departments and can be improved through further development of cross-cutting risk analysis initiatives along with more integrated policy development for implementing interventions. Systems thinking methods and competencies can also help to identify the multiple outcomes of interventions in terms of trade-offs and synergies (e.g. ICFS, 2017; EEA, 2020a; Oliver, 2021). Thus, participatory systems mapping to identify multiple risk cascades and intervention points, is not the end of the risk appraisal process, but instead the first step in a process which can also use system methods to help further refine and prioritise interventions.

Institutional capacity for systemic risk analysis

Taking these recommendations forwards will require a significant investment in systemic risk appraisal capacity. Cost-benefit analysis of such investments are tricky when the risks by definition cannot be easily defined in probabilistic terms. Yet, recent past experience alone shows how impacts such as Covid-19, air quality and food insecurity are hugely costly to a nation. Extending this to other types of systemic risk that are expected to materialise under rapid global change (Figure 1), and significant capacity building to appraise possible risk pathways and identify key watchpoints and interventions would seem a wise investment. Such capacity is likely best facilitated through national government, but should no doubt involve wide ranging inputs from different academic disciplines and representatives from key sectors and/or 'activity systems'. Furthermore, for the analysis of very complex risks surrounding wicked problems that involve value judgements, then involving representatives from the general public is also worth carefully considering (IRGC 2011, 2015 & 2018), in order to best capture plural values and perspectives as well as maximising cognitive diversity. The most appropriate 'knowledge architecture' (cf. Oliver et al., 2021) to build capacity in systemic risk assessment needs further consideration, but given the high likelihood and impact of many of these risks, there is urgency in moving forwards as soon as possible. We hope that this SysRisk project and the reflections on lessons learnt provides some useful input towards developing systemic risk assessment processes that might be valuable. These will need to be combined with lessons from other 'experiments', for example those that explore the best way to appraise the trade-offs and co-benefits, distributional (equity impacts), cost and feasibility of various interventions. Once again, given the wicked nature of these problems, it is likely that any approaches facilitated by national governments should also involve diverse participatory inputs.

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Further Reading

A selection of other reports on complex / systemic risk which may be of value to readers:

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Appendix 1: Detailed methodology and supplementary results

Selection of expert participants

Prior to the project the SysRisk team conducted research on expert elicitation research approaches, e.g. (Knol et al., 2010; EFSA, 2014; Hemming et al., 2018; O'Hagan, 2019). To ensure sufficient breadth of expertise, for each case study, a longlist of potential participants was developed by seeking people who had expertise in either the Political, Economic, Social, Technological, Legal and/or Environmental (PESTLE) aspects of their case study area (Figure 5). Participants were then selected for invitation by seeking a balanced representation of these PESTLE categories. Participants were contacted by email with an invitation and project information sheet and asked to return an Ethics consent form if they wished to take part. Ethical approval was received from the University of York Economics, Law, Management, Politics and Sociology ethics committee. The food system case study also considered representation from the food system activity areas of producing, processing/distributing, retailing, consuming and recycling/waste disposal. Twelve participants were initially recruited to each case study. On occasions where participants had to drop out of the project, additional experts were recruited to retain a balance of expertise across the six PESTLE categories.

Participants were scored by SysRisk team members in regards to their perceived expertise in terms of the PESTLE categories by allocating percentages across the seven categories. For example if a participant was deemed to be an equal expert in Economic and Social areas, but thought to have no expertise in other areas would be scored P = 0%, Ec = 50%, S = 50%, T = 0%, L = 0% En = 0%. To assess the balance of participants recruited to the project, participants were asked to score themselves using the above system. This allowed a comparison between the perceived and actual expertise recruited to the project (Figures 11-13 in the Reflections section and Table A1, below).

Anonymity of identity and affiliation of participants was not offered, because this was an expert elicitation study where participants were co-creators of the research and invited to co-author some outputs. However, meetings and workshops were conducted according to the 'Chatham house rule', where individuals are free to use information received, but not to reveal the identity or affiliation of the speaker or other participants. Discussions during the three workshops were not audio-visually recorded, but notes were taken by members of the SysRisk team that were only available to SysRisk team members.

Table A1, *Estimation of participant expertise across the PESTLE framework. Columns with subscript 1, e.g. P_1, indicate scores by the SysRisk project team. Columns with subscript 2, e.g. P_2, indicate participants' self assessment scores. Participants have been randomised within case studies.*

Participant	P_1	P_2	E_1	E_2	S_1	S_2	T_1	T_2	L_1	L_2	En_1	En_2
AQ1	0	NA	0	NA	0	NA	33	NA	0	NA	66	NA
AQ2	0	10	0	5	0	5	50	10	0	10	50	60
AQ3	0	NA	0	NA	0	NA	0	NA	0	NA	100	NA
AQ4	25	15	25	10	25	25	0	10	0	20	25	20
AQ5	50	35	0	0	0	0	0	10	0	10	50	45

AQ6	50	0	0	5	0	0	0	10	0	5	50	80
AQ7	33	22.5	0	5	33	22.5	0	5	0	22.5	33	22.5
AQ8	50	10	50	60	0	5	0	10	0	10	0	5
AQ9	50	20	0	0	0	0	0	0	0	20	50	60
AQ10	0	25	0	5	0	25	0	25	0	10	100	10
AQ11	0	NA	0	NA	0	NA	0	NA	100	NA	0	NA
AQ12	50	NA	0	NA	50	NA	0	NA	0	NA	0	NA
B1	10	NA	0	NA	10	NA	0	NA	80	NA	0	NA
B2	40	NA	0	NA	10	NA	50	NA	0	NA	0	NA
B3	0	10	20	5	0	5	80	65	0	5	0	10
B4	0	10	0	5	0	0	0	0	0	10	100	75
B5	0	NA	0	NA	20	NA	80	NA	0	NA	0	NA
B6	0	NA	0	NA	0	NA	60	NA	30	NA	10	NA
B7	0	NA	0	NA	50	NA	50	NA	0	NA	0	NA
B8	20	10	70	30	10	30	0	20	0	5	0	5
B9	0	NA	0	NA	30	NA	0	NA	70	NA	0	NA
B10	0	NA	80	NA	20	NA	0	NA	0	NA	0	NA
B11	0	20	0	20	0	15	0	15	0	5	100	25
B12	20	0	0	5	20	5	0	0	0	0	60	90
F1	10	NA	20	NA	10	NA	10	NA	10	NA	40	NA
F2	35	NA	10	NA	15	NA	10	NA	10	NA	20	NA
F3	10	NA	30	NA	5	NA	10	NA	5	NA	40	NA
F4	5	15	20	10	5	20	35	25	10	10	25	20
F5	20	25	10	0	25	10	10	25	25	30	10	10
F6	10	NA	25	NA	10	NA	20	NA	10	NA	25	NA
F7	15	NA	10	NA	15	NA	10	NA	15	NA	35	NA
F8	10	10	10	10	15	5	10	10	10	5	45	60
F9	5	20	30	20	10	15	10	15	10	10	35	20
F10	10	10	25	20	5	10	10	20	10	10	40	30
F11	10	20	10	10	50	60	5	0	15	0	10	10
F12	5	5	5	5	45	45	15	10	15	5	15	30

Inception Meeting

The SysSisk participatory process began on 29th April 2021, with an online inception meeting with all participants. The meeting provided details of the rationale behind the project and proposed workshop outlines. Participants were split into the three separate case studies groups for three subsequent online workshops. Workshop 1: an individual two hour workshop per case study occurring on the 15th (AQ), 16th (Bio) and 21st (Food) May. Workshop 2: an individual two hour workshop per case study occurring on the 13th (Bio), 14th (Air) and 15th (Food) September. Workshop 3: A combined one hour workshop on 17th November (Figure A1). There was also a stakeholder event on 16th Dec 2021 where this report was presented to a range of stakeholders involved in risk management (from government, business and third sector).

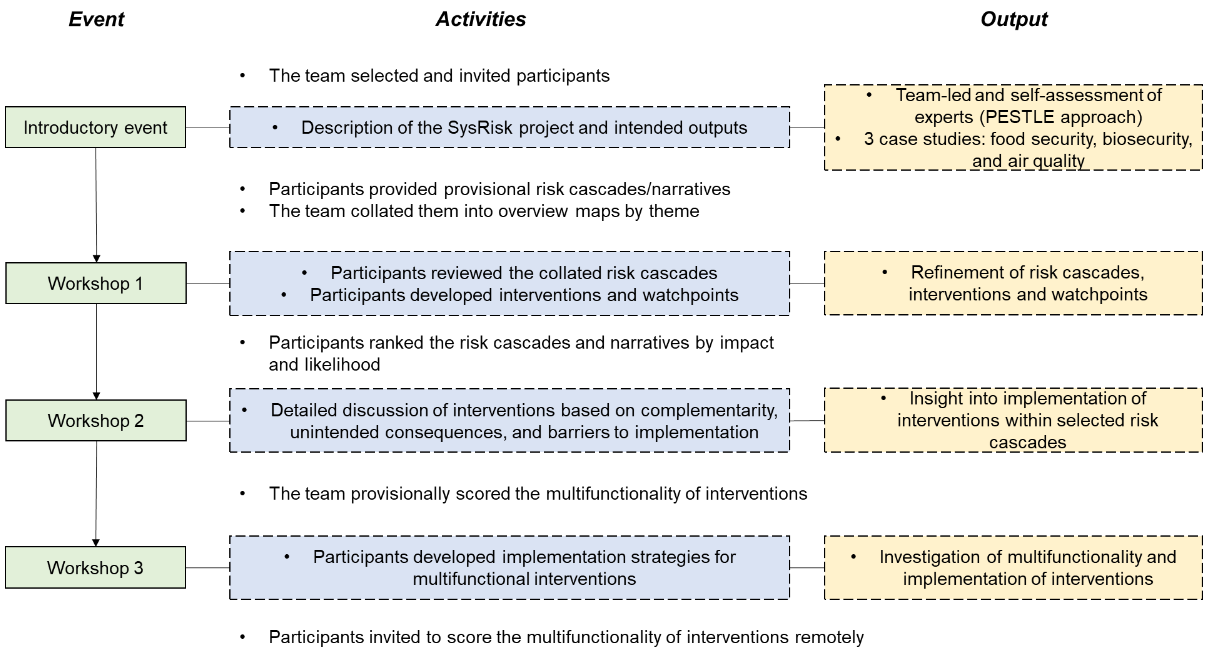

Figure A1, *The SysRisk meeting and workshop process across the three case studies*

Development of risk cascades, maps, interventions and watchpoints

Pre-workshop 1 task

Ahead of the first workshop, participants were asked to provide three short narratives or visual flow charts outlining potential risk cascades/scenarios that could result in negative health impacts to UK citizens, relating to their subject area. Participants were sent detailed instructions and an example (Figure A2; see also Figure 6 main report), with the option to use Participatory System Mapper (PRSM) software to draw the cascades. While the focus was on the UK, with the outcome on the right hand side of the cascade being negative health impacts on UK citizens, a consideration of global factors was encouraged. Participants were asked to consider at least one factor that had an environmental aspect. They were asked to be concise (i.e. not exhaustive in their narratives but to focus on key factors), and to include a statement regarding the timeframe of the narrative. Many of the cascades were highly interconnected, and were edited and amalgamated by the SysRisk team. Each case study created a number of separate maps grouped by broad themes, each containing multiple cascades. Finally, short narratives were written describing each particular risk cascade pathway included in the maps (see Project Output Directory).

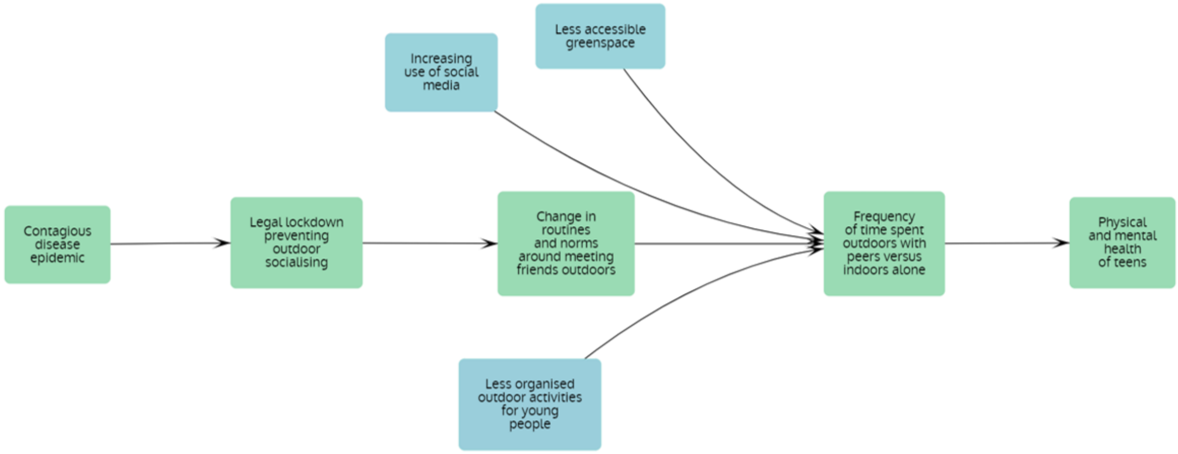

Figure A2, *Example flow chart produced using Participatory System Mapper (PRSM).*

For the air quality case study eight participants provided 18 risk cascades ahead of the workshop as either a diagram or a written narrative. SysRisk team members also provided nine risk cascades. These 27 contributed risk cascades were interconnected, and were edited and amalgamated by the SysRisk team to produce five large overview theme maps, broadly covering the areas of electric vehicles, climate change, resource pressure, novel pollutants, and work patterns (see Project Output Directory).

For the biosecurity case study, seven participants provided 19 risk cascades ahead of the workshop. These 19 contributed risk cascades were interconnected, and were edited and amalgamated by the SysRisk team to produce an overview map containing 14 cascades. This overview map was split into four theme maps, which broadly cover the areas of dormant pathogens, accidental or deliberate pathogen release, the human-livestock-wildlife interface, and post outbreak transmission scenarios (see Project Output Directory).

For the food case study, eight participants provided 24 risk cascades ahead of the workshop. Five SysRisk team members also provided 10 risk cascades. These 34 contributed risk cascades were highly interconnected, and were edited and amalgamated by the SysRisk team to produce an overview map containing 10 cascades. This map can be split into four sub-maps, which broadly cover the areas of production related factors (green), trade related factors (blue), pandemic related factors (pink) and economic and social barriers to nutritious food (orange; see Project Output Directory).

Workshop 1
Workshop 1 was case study-specific and lasted for two hours, beginning with a general introduction to all participants and for the remainder of the workshop participants were split into two groups. A total of nine participants from air quality, eight participants from biosecurity and 11 participants from the food case study attended, plus members of the SysRisk team. Each group spent 15 to 30 minutes on each of the theme maps, composed of amalgamated risk cascades (Tables 1-3) created for their case study. Participants were first asked to comment on and edit the factors and connections on the maps to improve accuracy and clarity. Participants initially worked individually to add interventions and data

watchpoints to the maps (Figure 6). There was then time to discuss and edit all the interventions and data watchpoints.

After the workshop, the SysRisk team amalgamated duplicate interventions and provided more depth and background information. The cascade maps were also adapted following participant changes and comments during the workshop. For the food case study, specific innovations from the National Food Strategy (Dimbleby, 2021) were added that were related to interventions added by participants, or that were raised during the workshop discussion.

Considering interventions in greater depth

Pre-Workshop 2 Task

Due to time constraints, it was not possible to carry out the next stage of the analysis on all 39 identified risk narratives. To prioritise which narratives would provide the most value in assessing, participants were asked to carry out a ranking exercise on each of the narratives from their case study (15 Air, 14 Bio, 10 Food) to determine their impact and likelihood. The questions scored on a scale of 1-5 as follows:

> ***What is the likelihood of the narrative occurring?***
> 1 = Possible: risk could materialise over the next 30 years but uncertain.
> 3 = Likely: risk is expected to materialise over the next 30 years, for example from modelling studies with high confidence.
> 5 = Certain/near-certain: risk is already being realised and is a current/past issue.
>
> ***What would the impact be if the narrative occurred?***
> 1 = Medium: risk expected to cause localised* minor health impacts (* < 0.25 UK population).
> 3 = High: risk expected to cause widespread non-fatal health impacts.
> 5 = Very High: risk could conceivably cause widespread* severe health impacts/loss of life over next 30 years (* > 0.25 UK population).

A total of 20 participants (9 Air, 4 Bio, 7 Food) returned results, along with an additional 4 (1 Air, 2 Bio, 1 Food) members of the SysRisk project team with relevant subject knowledge. The results across the two categories were averaged (mean) and plotted (Figure 7). Figure 7 was used as a guide to select four narratives to prioritise for the next workshop that were both high in impact and likelihood. Some additional judgement was used by the SysRisk team to select narratives. For example, for the food case study, two narratives that scored highly for impact (8 and 9 on Figure 7c) both related to the COVID-19 pandemic. Only one of these (narrative 9) was studied in greater depth during the workshop as it could be used to consider the wider issue of impacts of any future system shocks given reliance on food aid. In place of narrative 8 about pandemic specific risk cascade, narrative 5 regarding trade barriers was chosen as it had the next highest impact and likelihood score.

Workshop 2

In a two hour workshop participants were invited to assess the four prioritised cascades for their case study (Tables 1-3) and review the previously identified interventions. A total of 24 participants (12 Air, 6 Bio, 10 Food) plus SysRisk team members attended their respective workshops. Participants were split into two even groups, balanced across the PESTLE categories. Each group covered two of the four narratives and was given time to study the narratives and previously identified interventions as well as suggest if any interventions had been missed. Discussions were structured by facilitators to answer the following questions:

1. If all these interventions were in place to what extent would the risk be effectively reduced?
2. Are multiple complementary interventions needed?
3. In aggregate, what are the main barriers to putting effective interventions in place?
4. Are there unintended consequences of these interventions (and positive co-benefits)?

After the second workshop the narratives/cascades were reviewed and updated by the SysRisk team, incorporating the comments and suggestions made by participants. This included the addition and removal of factors and interventions. These can be found in the Project Output Directory (Tables 1-3).

Assessing multifunctionality and implementation of interventions

Pre-workshop 3 task

Each of the interventions across the final narratives/cascades were then assessed, initially by members of the SysRisk team and then by participants, to determine their levels of multifunctionality and implementation. Multifunctionality, in this sense, was defined as the ability of an intervention to simultaneously impact the other case studies, either as a co-benefit or a trade-off. This assessment was in two phases. First, individuals scored interventions from their own case study in regards to what extent they were being implemented using the following criteria:

- Yes - Existing policy framework in place, and/or significant business of third sector initiatives deemed to have significant impact.
- Partly - Part of current policy reform or planned initiatives; some initiatives in place by businesses/third sector.
- No - Some recognition of the problem and discussion of possible actions but negligible co-ordinated implementation.

Second, individuals reviewed interventions from the two other case studies to assess whether any of these interventions would have an impact on their case study e.g. would interventions identified in the air quality case study have benefits or trade offs for food security or biosecurity. Each intervention was given one of the following scores: -2 (strong trade off), -1 (weak trade off), 0 (no/very limited effect/s), 1 weak co-benefit, 2 (strong co-benefit). Where intervention impact was deemed to be highly context dependent an asterisk was added to the number e.g. 2*. The initial SysRisk team member scores for multifunctionality were used to identify examples of highly multifunctional interventions from each of the case studies (Tables A2, A3 and A4 & Figure 8). Overall frequencies across case studies are shown in Table A5. Examples of multifunctional interventions were:

- Food security: "Create new narratives around food and campaign to shift to healthier diets with lower environmental impacts".
- Biosecurity: "Support and encourage behavioural changes to reduce demand for animal products".
- Air quality: "Research into potential environmental degradation pathways of new chemicals before inclusion in products".

Table A2, *SysRisk team implementation and multifunctionality scores for interventions from the four risk cascades studied in detail (see Table 1) in the Air Quality case study. See table footer for explanation of scoring codes.*

Code	Intervention	Implemented	Bio	Food
A1	Close collaboration with EU and other programmes for approval processes and requirements (and/or ongoing consistent legislation)	Partly	0	0
A2	Designing products to last, and/or consuming fewer products	Partly	0	1
A3	Consider air-water-soil interaction in all environmental fate considerations, not just the medium into which the product is first released	No	0	2
A4	Reconsidering regulatory approach to a default of 'zero emissions' of any substances which change atmospheric composition	No	0	0*
A5	Use of research measurement techniques that capture many species to 'search' for those whose trends are changing (data mining)	Partly	0	0
A6	Further support for expert groups, including government advisory groups such as Air Quality Expert Group (AQEG) & Committee on the Medical Effects of Air Pollutants (COMEAP)	Partly	0	1
A7	Make horizon scanning/risk models for novel substances mandatory before production is permitted	Partly	0	0*
A8	Requirement to look at potential environmental degradation pathways of chemicals before inclusion in product	Partly	1	1
A9	Collaborate with health research. For example, finding novel air pollutants in compromised body systems, such as links between Alzheimer's and ultrafine PM	Partly	0	1
A10	Impose regulatory ban/limits on novel pollutant on basis of precautionary principle	Partly	0	0*
A11	Require Local Air Quality Management (LAQM) & industrial regulation to consider emerging issues	No	0	1*
A12	Question paradigm of electric vehicles being the best solution to transport		0	0
A13	Scrappage/ incentive scheme to encourage fleet turnover	Partly	0	1*
A14	Awareness raising campaign about the impact of traditional vehicle life cycle emissions	Partly	0	0
A15	Increase in consistent and universal charging point network	Partly	0	0
A16	Encourage walking routes away from roads	Partly	0	1*
A17	Improve walking routes, including safety (& perception of safety)	Partly	0	1*
A18	Addressing local government capacity issues to implement ambient air quality safe school zones	Partly	0	0
A19	Tree planting to intercept roadside pollutants	Partly	0	0
A20	Urban design to reduce personal car use and increase pedestrian walkways and green spaces	Partly	0	1*
A21	Geo-engineering (need to give examples)	No	0	0*
A22	Regulate industrial and domestic water use	Partly	0	0*
A23	Nature-based solutions (e.g. green space/vegetation) for alleviating heat island effects	Partly	0	2
A24	Improve efficiency of air conditioning via regulation and education	Partly	0*	0
A25	Use of factory constructed modules in construction (modular construction of housing)	Partly	0	1*
A26	Develop new best practice measures, in light of predicted changes (for example, the	Partly	0	0

	control of dust and emissions from construction and demolition)			
A27	Better design and mitigation to reduce dust generation.	Partly	0	0
A28	Collation and sharing (& legal requirement) of best practice for construction	Partly	0	1*
A29	Coordinated planning conditions for construction activities across a local area	No	0	1*
A30	Best Practice in construction, eg Institute of Air Quality Management (IAQM) or Greater London Authority (GLA) as standard in UK	Partly	0	1*
A31	Reduction in working hours to enable more time for exercise	No	0	1*
A32	Climate change policies (path to net zero, UK climate change act 2008)	Partly	2*	2
A33	Education on alternative ways to cool homes besides air conditioning units	Partly	0	0
A34	Stricter regulation on energy efficiency of domestic appliances, beyond the Ecodesign Directive	Partly	0	0
A35	Combined approaches (vent + air purifying + masks) to tackle COVID	Partly	1	1
A36	Increased research on toxicity of household chemicals, including combinations, plus better regulation	Partly	0	0
A37	Consider air pollutants as well as CO2 in net zero decisions		0	1
A38	Education campaign on improving indoor air quality	Partly	1	1*
A39	Develop health impact assessment methods to assess exposure	Partly	0	0
A40	Regulate exposure rather than concentration	No	0	0
A41	Better building design	Partly	1	1*
A42	Downsize offices and encourage hot-desking	No	1	0
A43	Renewed campaigns for home energy efficiency		1*	0
A44	Address tensions between insulation and ventilation (insulation supports energy efficiency vs ventilation helps with indoor air pollution, exposure & Covid)		1	1

Code refers to the allocations in Figure 8. Implemented classified as: Yes - Existing policy framework in place, and/or significant business of third sector initiatives deemed to have significant impact; Partly - Part of current policy reform or planned initiatives; some initiatives in place by businesses/third sector; No - Some recognition of the problem and discussion of possible actions but negligible co-ordinated implementation. Multifunctionality scored as: -2 (strong trade off), -1 (weak trade off), 0 (no/very limited effect/s), 1 weak co-benefit, 2 (strong co-benefit). Where intervention impact was deemed to be highly context dependent an asterisk was added to the number e.g. 2*

Table A3, *SysRisk team implementation and multifunctionality scores for interventions from the four risk cascades studied in detail (see Table 2) for the Biosecurity case study. See table footer for explanation of scoring codes.*

Code	Intervention	Implemented	Air	Food
B1	Improve the quality of information regarding disease outbreaks provided to the public making use of research based in this area, in order to reduce confusion and misinformation on the subject	Yes	0	1
B2	Improve communication strategies to raise awareness of zoonotic disease drivers, with specific messaging used for different sectors of the population in order to further educate the public on disease risks.	Partly	0	2
B3	Counter dis, mis and mal information (DMMI) operations to protect the narrative around disease outbreaks, pandemic risk and health interventions	Yes	0	1
B4	Increase international cooperation to tackle bioterrorism.	Yes	0	1
B5	Increase security in research labs and increase the regularity of biosecurity inspections to reduce the likelihood of biological agents escaping (either accidentally or deliberately).	Yes	0	0*
B6	Improve detection and response capabilities for the misuse of biotech to reduce the ability of individuals to attain and use bio-weapons. Create a deterrent by denial effect.	Yes	0	0
B7	Increase the awareness and understanding within the police and intelligence services of possible bioterrorism activities and enhance ability to prevent events e.g. monitoring of suspicious activity indicative of bioterrorism.	Partly	0	0
B8	Integration of UK Intelligence Community (high side) intelligence sharing with non-traditional security departments e.g. DEFRA, in order to better identify biological threats such as the acquisition and use of bioweapons.	Partly	0	1
B9	Better training of workers to encourage a culture of transparency to ensure the escape/theft of biological agents is not covered up or goes unnoticed.	Yes	1*	0
B10	Increase controls on the regulation of access to biotechnology and improve the targeting of regulation to restrict the access and use of biotechnology. This would ensure those using biotechnology are vetted and do not pose a credible threat.	Yes	0	0
B11	Improve regulation and licencing to assist replacement of animal products that pose a high disease risk with alternatives to reduce the likelihood of disease outbreak.	Partly	1*	2
B12	Support and encourage behavioural changes to reduce demand for animal products.	Partly	2	2
B13	Innovation into food production with a lower footprint e.g. vertical agriculture to reduce the need for habitat disturbance/destruction.	Yes	1	2
B14	Enhance commons management systems and cooperation in land use governance	No	1	2
B15	Improve regulation of international standards to reduce or ban long distance movements of livestock, in order to reduce risk of disease spread during livestock transport.	Partly	1	0*
B16	Improve tracking of livestock provenance and associated biosecurity standards, in order to reduce risk of disease spread during livestock transport.	Yes	0	2
B17	Climate change mitigation measures e.g. divest from fossil fuels in line with Paris Climate Agreement to keep warming below 1.5°C, in order to reduce the risks of emerging infectious diseases associated with climate change.	Partly	2*	2
B18	Harmonise global standards for animal transportation (via World Trade Organisation), in order to reduce the risk of disease spread during livestock transport.	Partly	0	0*
B19	Set (review) maximum stocking/congregation density for all animals in order to reduce the likelihood of disease spread during livestock rearing.	Partly	1	0*
B20	Improve on site farm biosecurity to restrict contact between livestock and wildlife in order to reduce the transfer of disease from wild species into livestock.	Partly	0	0*
B21	Greater training of veterinary and medical professions to identify causes of death and symptoms of diseases in livestock that have concern for human health.	Partly	0	2
B22	Restrictions in the use of antibiotics in farming to reduce the risk of antibiotic resistance.	Partly	0	1

B23	Research into antimicrobial resistance in fungi/bacteria that improves cost effectiveness for farming methods.	Partly	0	2
B24	Targeted surveillance of livestock for known zoonotic pathogens to increase the likelihood of catching disease outbreaks before they spread further.	Yes	0	1
B25	Improve widespread bio-surveillance employing metagenomic sequencing to increase the likelihood of catching disease outbreaks before they spread further.	Partly	0	1
B26	Increase provision of PPE and equipment to improve hygiene standards in the livestock sector to reduce the likelihood of diseases in livestock transferring to humans.	Yes	1*	1
B27	Increase research into understanding the basis of species barriers to guide legislation around professions working with animals.	Yes	0	1
B28	Monitoring for vectors around points of introduction to reduce the likelihood of diseases being introduced into areas.	Yes	0	1
B29	Improve/develop Environmental Risk Assessment & related regulations to reduce the risk of disease transfer/spread	Yes	1*	2
B30	Increase/review research into host/vector ecosystems prior to commencement of infrastructure projects (using previously existing projects as natural experiments) in order to understand (and mitigate) the effect such projects could have on disease risk.	No	0	0
B31	Greater training of veterinary and medical professions to identify cause of death and symptoms of diseases in wildlife that have concern for human health	No	0	2
B32	Reduce human contact with wildlife by tackling socioeconomic factors that result in the need for bushmeat hunting, deforestation etc. to reduce human wildlife interactions and the associated disease risk.	Partly	0	0*
B33	Increase provision of PPE and equipment to improve hygiene standards of industries in contact with wildlife to reduce the likelihood of diseases in wildlife transferring to humans.	Partly	0	0*
B34	Identification of high risk zones for disease emergence and introduction of new guidelines to reduce disease risk in these areas.	Partly	0	1
B35	Monitor new species/hybrids (via sequencing) to determine changes to disease risk.	Yes	0	1
B36	Boost healthcare systems through investment in infrastructure to better prepare for pandemics.	Partly	-1	2
B37	Improve selective targeting of individuals required to isolate to reduce the need to lock-down.	Partly	0	1
B38	Increasing trust between communities and healthcare systems to increase the uptake of vaccines /adherence to healthcare policies	Yes	0	2
B39	Increase health system funding to increase capacity to deal with pandemics.	Partly	0	2
B40	Improve ventilation in housing to reduce disease transmission.	Partly	2	1
B41	Better design in new housing developments to improve ventilation needs and reduce disease transmission.	Partly	2	1*
B42	Retrofit current housing to improve ventilation needs and reduce disease transmission.	Yes	2	1*
B43	Stress relevant hygiene measures to reduce disease transmission.	Partly	0	1
B44	Support for those not in 'conventional' work; increase paid sick leave to reduce infected individuals working out of necessity and spreading disease.	Partly	0	1
B45	Interventions that ensure household isolation (including not attending work) is not financially damaging to reduce infected individuals working out of necessity and spreading disease.	No	0	2
B46	Allow for multigenerational households in public housing to avoid crowding and reduce disease transmission.	Partly	0	2
B47	Improve communication between departments/organisations to ensure that individuals (e.g. health care professionals) are not moving between health care providers unnecessarily.	Partly	1	2
B48	Better training of health care providers to reduce the likelihood of disease transmission whilst providing health care.	Yes	1*	1

B49	Develop improved therapeutics to reduce the impact of disease.	Yes	0	0*

Code refers to the allocations in Figure 8. Implemented classified as: Yes - Existing policy framework in place, and/or significant business of third sector initiatives deemed to have significant impact; Partly - Part of current policy reform or planned initiatives; some initiatives in place by businesses/third sector; No - Some recognition of the problem and discussion of possible actions but negligible co-ordinated implementation. Multifunctionality scored as: -2 (strong trade off), -1 (weak trade off), 0 (no/very limited effect/s), 1 weak co-benefit, 2 (strong co-benefit). Where intervention impact was deemed to be highly context dependent an asterisk was added to the number e.g. 2*

Table A4, *SysRisk team implementation and multifunctionality scores for interventions from the four risk cascades studied in detail (see Table 3) for the Food Security case study. See table footer for explanation of scoring codes.*

Code	Intervention	Implemented	Bio	Air
F1	Initiatives to increase nature connectedness, awareness of drivers of climate change and awareness of purchasing impacts	No	1	2
F2	Accredited and transparent environmental food labels.	Partly	1*	1*
F3	Create new narratives around food and campaign to shift towards diets with lower environmental impacts.	No	1*	2
F4	Education and communication strategies for intergenerational knowledge and 'remembering' (i.e., pre-war agriculture/wildlife soundscapes')	No	0	0
F5	Shift attitudes from food consumers to food citizens and incorporate a right to accessible nutritious food into policy making.	No	1*	0
F6	Maintain pressure for global government and corporate actions to rapidly reduce emissions to limit global heating to 1.5 degrees and to mitigate the current and future health impacts and loss of life from climate change, land use change and biodiversity loss.	Partly	2	2
F7	Shift mindsets from the cheaper food paradigm and yield based productivity of individual crops, towards long term resilience and whole system based productivity.	No	1*	0
F8	View food production as a service rather than a commodity, where producers and consumers share the risk and reward.	No	1*	1*
F9	Appropriate metrics for global warming potential (GWP equivalent) from different food sources.	Partly	0*	1
F10	Fiscal incentives and credit availability to tackle climate change.	No	1	1
F11	Create carbon pricing including border carbon adjustments to influence land use, reduce emissions and their impacts, de-incentivise land use conversion, and change diets through food prices.	No	2	1
F12	Limit land use change through sustainable intensification of existing land use, densification of growing systems (e.g vertical farming, CEA)and reduced meat consumption.	No	2	2
F13	Increase UK grown plant protein, e.g. nuts, legumes	No	1	0*
F14	Create a rural land use framework and improve the use of data to prioritise land use for nature, carbon sequestration and food production in order to support local decision making.	No	0	1
F15	Improve the research, support and framework for on-farm and supply chain monitoring and reporting of environmental metrics.	No	1*	2
F16	Introduce more diverse systems, with longer rotations, including livestock into UK agriculture/horticulture.	Partly	1*	0
F17	Fund and support more research on resilient agro-ecological farming - rather than investing only in commodity crop yields.	No	1*	0
F18	Monitor the implementation of Environmental Land Management Schemes for impact on ecosystem services in England and Wales.	Partly	0*	1
F19	Maintain at least the current agricultural budget until 2029 to support transition into ELMs. Ensure that payment for public goods is at a level that improves farmer/grower incomes without the need for intensification.	No	0*	0
F20	Change public funding to better reward the production of fruit and vegetables.	No	0	0
F21	Set reasonable goals for soil health and carbon sequestration.	No	1*	1

F22	Improve training and peer to peer networks that research and promote regenerative practices and business models.	No	0	0
F23	Integrate trees into farming systems.	Partly	1*	1
F24	Increased investment in research and communication on the link between soil health and human gut health and disease prevention.	No	0	0
F25	Improve government data consistency across Arms Length Bodies on farm and across the food chain.	No	0	0
F26	Create more parity in the food chain relating to profit margins.	No	0	0
F27	Strengthen public procurement rules for sourcing healthy and sustainable food locally, or that is compliant with UK standards.	Partly	1*	0*
F28	Define core minimum environmental, health and animal welfare standards for future trade deals and set out mechanisms to protect these, as recommended by the Trade and Agriculture Commission.	No	1	1
F29	Relocalise UK production (particularly fruit and veg) and provide more support for domestic production.	No	0	1
F30	Include recommendations from the Trade and Agriculture Committee when negotiating trade deals and enact Government consultations.	No	1*	1
F31	Increase parliamentary scrutiny, media reporting and non-governmental analysis of Government policies and spending impacting on climate and food systems.	No	1*	0*
F32	Align trade ambition with UK production capability and health aims.	No	1	0
F33	Increase investment in AgriTech, Controlled Environment Agriculture, urban horticulture and building integrated horticulture.	Partly	1*	0
F34	Increase investment in UK horticultural innovation (particularly social-innovation) and training.	No	0	0
F35	Develop integrated planning policy that actively supports very low impact agriculture and associated housing developments e.g. One Planet policy in Wales	No	0	1
F36	Work with The Institute for Agriculture and Horticulture (TIAH) and grassroots organisations to investigate how agricultural/horticultural work and careers could become more attractive to British workers e.g. local, part-time careers, training.	No	0	0
F37	Change immigration and worker immigration rules to increase labour availability.	No	0	0
F38	Increase the pace of automation in production, processing and retail.	Partly	0	0
F39	Address planning and economic barriers to on farm housing, affordable rural housing, urban horticulture and building integrated horticulture.	Partly	0	0
F40	Create a structured system for allocating a pool of labour across a variety of industries and/or organisations in response to system shocks.	No	1	0
F41	Improve central, devolved and local Government knowledge, systems and readiness for preventing and responding to food insecurity risks and emergencies (both long term and shocks) with resources, manuals, training and delivery mechanisms.	Partly	1	0
F42	Create contingency Plans that span across non-traditional response orgs (Local Resilience Forums) to include volunteer recruitment campaigns	Partly	1	0
F43	Improve support for part-time farming careers allowing people to be available for seasonal farming work without having to give up current work	No	0	0
F44	Increase the use of Volunteer Reserves (Armed Forces) in UK Resilience	Partly	1	0
F45	Either reinstate real food stores (as per cold war, or Brexit planning), or develop virtual food stores like a flexible biofuel mandate (when prices rise, switch grain for energy into grain for food).	No	1	0

F46	Provide greater policy support for domestic food production so it can respond to a crisis.	No	1	0*
F47	Provide rapid start-up funding for essential businesses.	No	0	0
F48	Create business systems that can rapidly change sales and distribution models.	Partly	0	0
F49	Create geopolitical early warning systems, especially of global 'breadbaskets'.	Partly	0	0
F50	Invest in institutions and programmes to monitor and research emerging diseases.	Yes	2	0
F51	Collaborative UK agricultural demand planning from major retailers and food manufacturers who source in UK.	No	0	0
F52	Introduce rationing	No	0	0*
F53	Range rationalisation by major retailers in response to shocks	Partly	0	0
F54	Redundancy/extra capacity support to respond to system shocks	Partly	0	0
F55	Tackle systemic causes of poverty and legislate for a real living wage.	Partly	1*	1
F56	Join up agricultural and horticultural policy e.g. public money for horticultural businesses/community food growing that provide community mental & physical health benefits.	No	0	0
F57	Interventions to build community food resilience.	Partly	1	0
F58	Interventions to improve community transport.	Partly	0	1
F59	Support new hybrid business models that deliver social and economic outcomes. Introduce incentives and preferential business rates for these types of business models.	Partly	0	0
F60	Greater financial and practical support for Community Supported Agriculture and other Community Interest business models, particularly in low income areas.	Partly	0	0
F61	Enable community based organisations to tackle affordability and access to nutritious food e.g. US initiatives such as wholesome wave.	Yes	0	0
F62	Develop a more holistic set of indicators to monitor food insecurity and health outcomes.	Partly	0	0
F63	Improve watchpoints and the availability and marketing of healthy food by introducing mandatory reporting from large food companies of value and volume of sales of fruit and vegetables, proteins by type and origin, foods high in fat, salt and sugar and of food waste.	Partly	0	0
F64	Introduce clearer culturally sensitive food guidelines and education, based on portions, meals, and commensality of food beyond simplistic recommendations of proteins, carbohydrates and fats.	Partly	0	0
F65	Require a whole school approach to food and extend eligibility for free school meals and funding of the Holiday Activities and Food programme.	Partly	0	0
F66	Government introduce a tax on sugar and on salt sold for use in processed foods or in restaurants and catering businesses	No	0	0
F67	Expand the healthy start voucher scheme to improve access to fruit and vegetables for families on a low income.	Partly	0	0
F68	Use social prescribing to improve access to fruit and vegetables through vouchers, education and support for people on low incomes.	No	0	1
F69	Re-establishing and linking multi-cultural, pan-generational food histories focusing on the 'old ways' of working with less food technologies	No	0	0

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Table A5, *The frequency of multifunctional interventions across food security, air quality, and biosecurity case studies. Multifunctionality is defined here as the ability of an intervention to simultaneously impact the other case studies, either as a co-benefit or a trade-off. Summarised here are scores assessed directly by the SysRisk team. Shown are the number of interventions and percentage of the total for each case study.*

	Air quality (n=44 interventions)		Biosecurity (n=49 interventions)		Food security (n=69 interventions)	
Assessment of multifunctionality	Biosecurity	Food security	Air quality	Food security	Biosecurity	Air quality
Strong co-benefit	1 (2%)	3 (7%)	4 (8 %)	17 (35%)	4 (6%)	5 (7 %)
Weak co-benefit	6 (14%)	7 (15%)	5 (10%)	17 (35%)	12 (17%)	14 (20%)
Limited effect	35 (80%)	17 (39%)	33 (68%)	5 (10%)	35 (51%)	43 (63%)
Weak trade-off	0 (0%)	0 (0%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)
Strong trade-off	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Context dependent	2 (4%)	17 (39%)	6 (12%)	10 (20%)	18 (26%)	7 (10%)

Workshop 3

The interventions identified as highly multifunctional (Tables A2-5) were further reviewed in a third workshop lasting one hour. All project participants attended a single meeting. After a 15 minute general introduction participants (11 Air, 5 Bio, 10 Food, plus nine members of the project team) were allocated into breakout groups of their own respective expertise in order to work on implementation strategies for interventions. In each group, participants used the software Mural to work on implementation strategies for a single, multi-functioning intervention. The exercise involved describing specific ways to implement the respective interventions to leverage systemic change. Participants were asked to consider specific aspects, including: enablers and barriers for implementation, potential negative impacts, who are the actors and stakeholders responsible for implementation, and winners and losers if the intervention was implemented.

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