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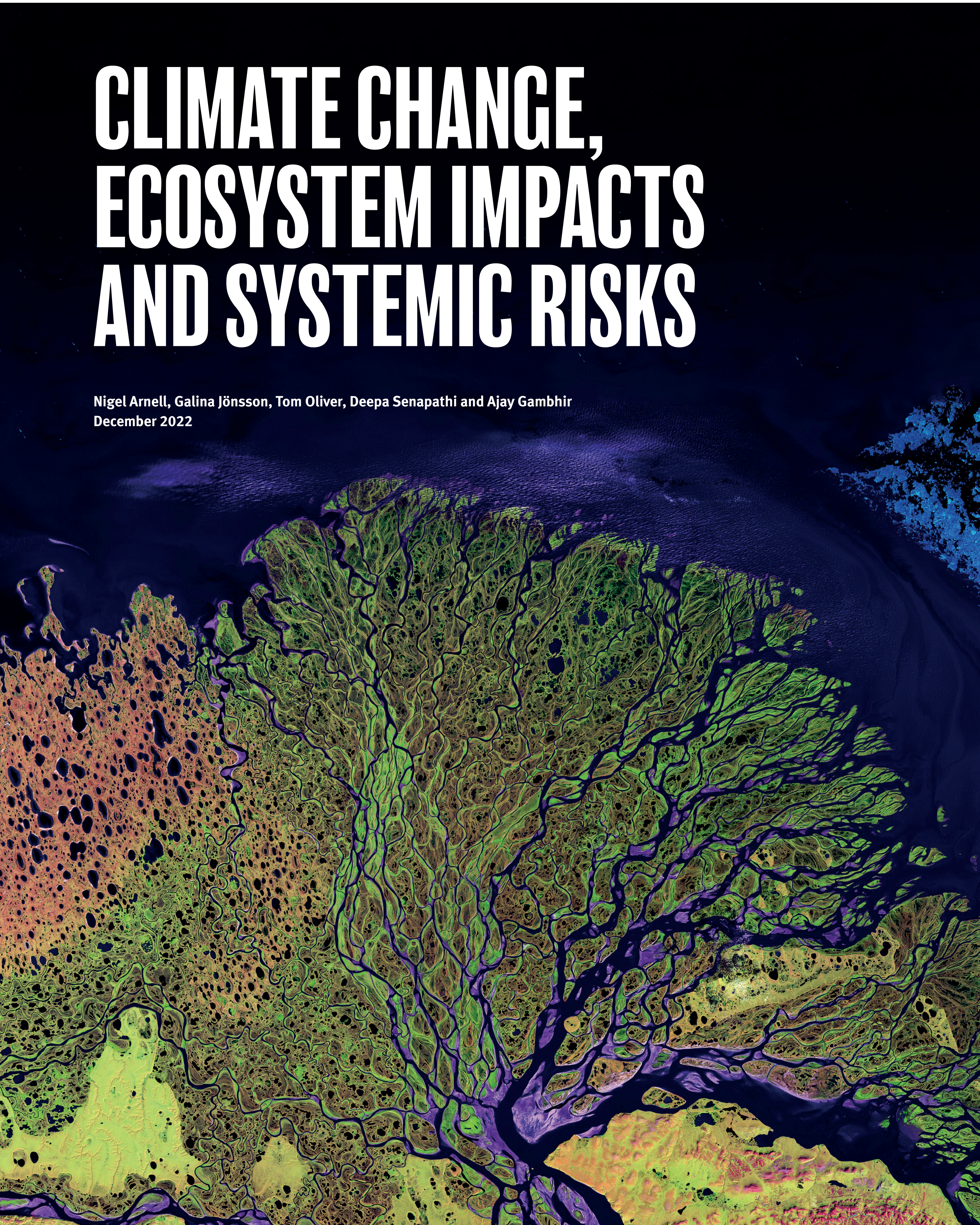

CLIMATE CHANGE, ECOSYSTEM IMPACTS AND SYSTEMIC RISKS

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SUMMARY

Politicians, strategists and environmental campaigners are increasingly concerned about the potential for climate change to create major systemic risks with extreme – and controversially existential – consequences.

These systemic risks may be triggered not only by the direct physical impacts of climate change – on heatwaves, floods, fires and drought – but also by the effects of ecosystem changes generated by climate change. However, there have so far been very few robust analyses of systemic risks under different future emissions pathways. Moreover, whilst there have been several studies of direct physical risks, there are very few studies into ecosystem changes in terms directly relevant to human systems. This is partly because ecosystems are inherently difficult to model because they are based on complex inter-relationships, and partly because most studies have concentrated on indicators relevant to ecosystems in themselves.

This report presents a review of the evidence available to support the robust assessment of the potential for ecosystem changes to trigger regional and global systemic risks. Such a robust assessment must involve a blend of quantitative information on relevant indicators calculated under different emissions pathways with expert judgment on how changes in exposure and vulnerability translate impacts into systemic risk. Ecosystem changes have the potential to generate regional and global systemic risk both through changes occurring over large areas and through changes occurring in particularly sensitive locations. Information on the effects of ecosystem changes should therefore be incorporated into this approach in two ways: using relevant high-level global-domain indicators combined with expert judgment on implications for human systems, and using expert judgment to identify critical sensitive locations and use locally-relevant indicators to infer impacts on ecosystems and systemic risks.

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1. INTRODUCTION

Over the last few decades, climate researchers have demonstrated that climate change will increase significantly the frequency or magnitude of heatwaves, droughts, floods, wildfires and storms, and substantially alter the climate resources available to agriculture and ecosystems.

Many of these direct risks have been quantified – albeit with considerable uncertainty – and in many instances have been expressed in terms of the numbers of people or area of land affected. Increasingly, both the public and policymakers have expressed concern over potential large-scale existential risks posed by climate change to societies and economies, and also the effects of major ecosystem changes on these risks. However, there have so far been very few robust assessments of such 'systemic' risks – risks that affect a system as a whole - and how they might vary with different pathways for future emissions. The recent IPCC Working Group 2 report (IPCC, 2022) describes complex, compound and cascading risks – where one risk leads to another - but does not specifically assess systemic risks. Most descriptions of potential systemic risks are very speculative and are sensitive to assumptions about social and political responses to climate change and therefore context. Some use empirical relationships between drivers and complex risks that are highly dependent on data and methods used and underplay the role of choices and decisions in determining how change results in systemic risk. A more robust assessment would combine consistent quantitative information on the range of risks and changes that might generate systemic risks with informed qualitative or narrative characterisations of how social, economic and political systems respond and react to change.

This report represents part of the development of a robust methodology for the assessment of regional and global systemic risks with different pathways of future emissions which lead to different levels of global warming: the assessment itself is seen as a contribution to a larger activity to understand what aspects of social, economic and political systems dampen or enhance regional and global systemic risks, and what governance mechanisms might be effective at reducing the systemic risks posed by climate change. The report uses a lens of ecosystem changes to explore systemic risks, because there is an emerging, yet still nascent, literature on the dependence of human systems on, and risks posed to them by, ecosystems, which remains critical yet underexplored. Specifically, this report concentrates (i) on how ecosystem changes driven by climate change might, in combination with the direct effects of climate change, lead to systemic risks to human social and economic systems, and (ii) on relevant indicators of ecosystem change that could be calculated with climate change scenarios to provide evidence to support robust assessment of climate risks. The report is based on a substantive review of the published literature and recent assessments (IPBES, 2019; Parmesan et al., 2022; Cooley et al., 2022).

> ***Increasingly, both the public and policymakers have expressed concern over potential large-scale existential risks posed by climate change to societies and economies, and also the effects of major ecosystem changes on these risks.*** ”

It is first necessary to outline a framing for the characterisation of systemic risks, because this affects the development of an overall methodology.

2. SYSTEMIC RISKS: A FRAMING

A ‘direct’ risk of climate change is a specific impact on a specific part of a system which can be directly attributed to weather or climate, such as a drought affecting crop production or a heatwave affecting human health (King et al., 2015).

It can be characterised in biophysical terms – the magnitude of a drought index or number of days with temperature exceeding some threshold, for example – or in human terms such as the reduction in crop growth or numbers of people suffering ill-health.

A systemic risk, in contrast, is one which affects the integrity of a system as a whole (e.g. Centeno et al., 2015; Renn, 2016; Renn et al., 2019), and is the consequence of the nature of linkages between parts of the system. The concept of systemic risk was introduced in the financial sector and most empirical studies therefore come from that sector, but the concept has since been applied more widely (see Robinson et al., 2018; Li et al., 2021). The scope of a systemic risk depends on the definition of the system of interest (from ‘the transport system’ for example to ‘the world economic system’), but the key point is that a systemic risk is much more consequential than a direct risk.

> ***Systemic risks generated by climate change are different because climate change will generate a number of acute shocks (“black swans[1]”) superimposed on a longer-term chronic change*** ”

Scale is important in three ways. First, a system at a place may be vulnerable to pressures and challenges from a much larger geographic area. For example, food price shocks in a place may be driven by production shocks elsewhere. Second, a systemic risk in one location may feed into risks elsewhere through larger higher-level linkages. For example, an increase in local insecurity may overflow to other countries through population displacement. Third, a systemic risk could directly affect some global system – for example widespread crop failures affecting global food markets. The focus here is on systemic risks which generate an international response: this can be through a local risk with international consequences, or a risk that arises in several places at once.

In business, political and military terms, a systemic risk is typically seen as a cascading consequence of an external shock (a “domino effect”: Aglietta, 2003). Systemic risks generated by climate change are different because climate change will generate a number of acute shocks (“black swans”) superimposed on a longer-term chronic change (for example in the climatic suitability for agriculture) which may push systems into failure (“grey rhinos”[1]). These acute shocks and chronic changes are occurring across the world, and both vary from place to place and are geographically connected. Climate change is also superimposed onto other pressures and changes, such as increases in population, economic development pressures, increasing economic inequality,

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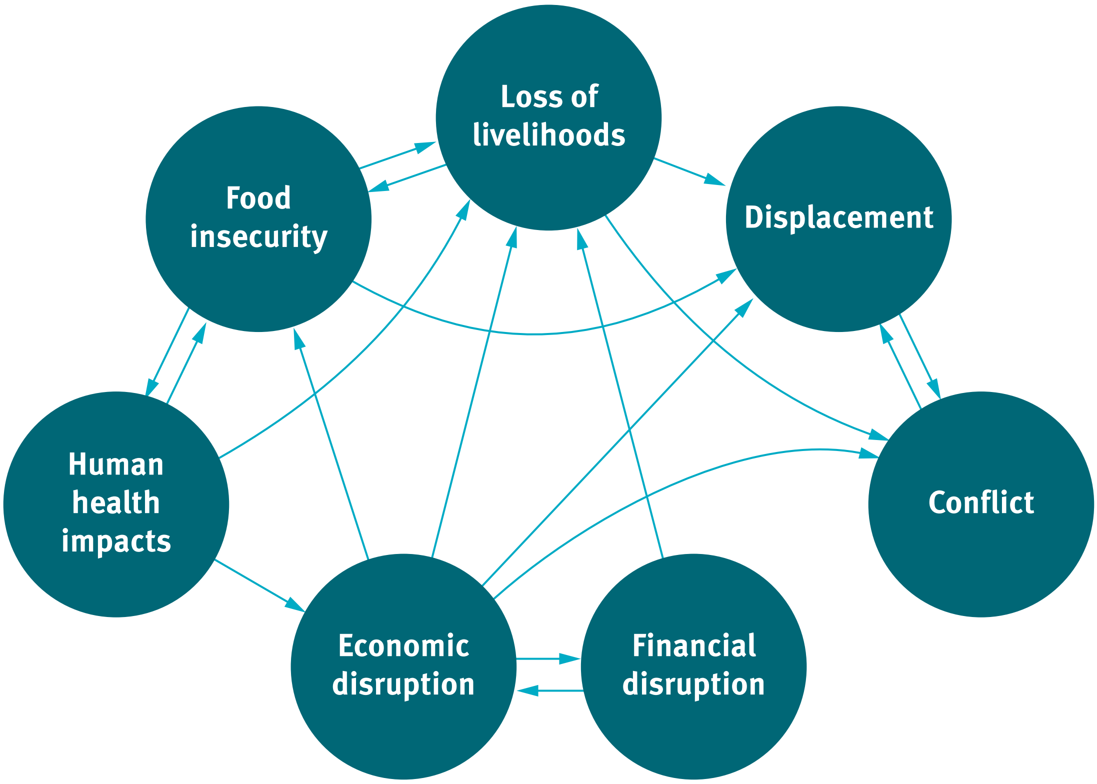
[1] *A ‘black swan’ is an unexpected event, whilst a ‘grey rhino’ is an obvious risk that creeps up but is neglected despite its size and likelihood*

Figure 1: A characterisation of systemic risks



land use change, and geopolitical instability, and can potentially exacerbate them: in other words, it is a threat multiplier. Li et al. (2021) also distinguish between serial and parallel cascades, and define a ‘nexus risk’ as occurring when two or more types of risks are associated and interact with each other.

A second key point is that systemic risks are conceived here as being largely a function of the characteristics of the system rather than the nature of the external shock (they are endogenous rather than exogenous: this is a central tenet of the concept of the ‘risk society’: Beck, 1992). The characteristics of the system of interest, how various components link together, and how actors within the system respond to shocks or pressures are therefore extremely important. Together they determine the extent to which a given direct impact translates into a systemic risk: they determine resistance and resilience. A key implication is that small shocks can generate large systemic risks, and similarly that large shocks may trigger little response.

There are many potential ways of describing systemic risks, and Figure 1 shows one characterisation. This identifies seven linked domains of systemic risk – food production failure (i.e. food insecurity), human health, loss of livelihoods, economic disruption (including resource depletion), disruption to the finance system, displacement and conflict (Li et al. (2021) define five different domains, but the principles are similar). Other domains may also be relevant at the local scale. All the domains are linked to climate change, although the strength of the link varies between domains. Conflict, for example, is linked to economic disruption and resource depletion, loss of livelihoods and displacement rather than the immediate effects of climate change, but it is possible to build convincing stories linking all the other domains to climate change. Figure 2 (developed from Robinson et al., 2018) shows an example of the links between direct and systemic risks, emphasising (i) the multiple potential climate shocks and (ii) the importance of factors determining exposure and vulnerability in generating systemic risks.

3. ASSESSING SYSTEMIC RISKS

Several high-level frameworks for assessing systemic risk have been proposed (including Li et al.'s (2021) characterisation of risks in terms of impact domain, severity and likelihood), but to follow these in practice it is necessary to analyse risks in a robust and systematic way.

Whilst it is in principle possible to estimate quantitatively the direct risks of climate change under specific assumptions about future emissions and exposure (albeit with some major methodological issues for some indicators of risk), it is much more challenging to characterise and evaluate quantitatively systemic risks. This is because they depend on the complexity of how a system operates and on actions and decisions taken by key actors – which may depend on actions taken by other actors. Quantitative models describing future systemic risk cannot be empirically tuned on past experience using data analytics, because the past is not necessarily a good guide to the future. However, empirical evidence from the past can be used with expert judgement to create hypotheses and models describing linkages: Richards et al. (2021) used this approach to create a Causal Loop Diagram (CLD)[2] linking climate change, food insecurity and societal collapse.

In order to robustly assess possible future systemic risks, it is therefore necessary to combine expert judgment on system behaviour and actor response under well-specified socio-economic and political scenarios with consistent quantitative information on direct risks to which the system is exposed to produce credible narratives or stories. The expert judgment on behaviour and response could be developed through analysis of past events (as done by Richards et al., 2021) and through brainstorming and qualitative scenario and 'what-if' analysis. The underpinning quantitative part of the assessment requires the estimation of the suite of direct risks which might affect the system, using consistent assumptions about future emissions, patterns of change in relevant dimensions of climate, and exposure. These are characterised

> ***Changes in just a few key species could potentially impact whole ecosystems, due to the linkages across ecosystem networks***

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[2] *A device for visualising relationships between variables and states in a complex system*

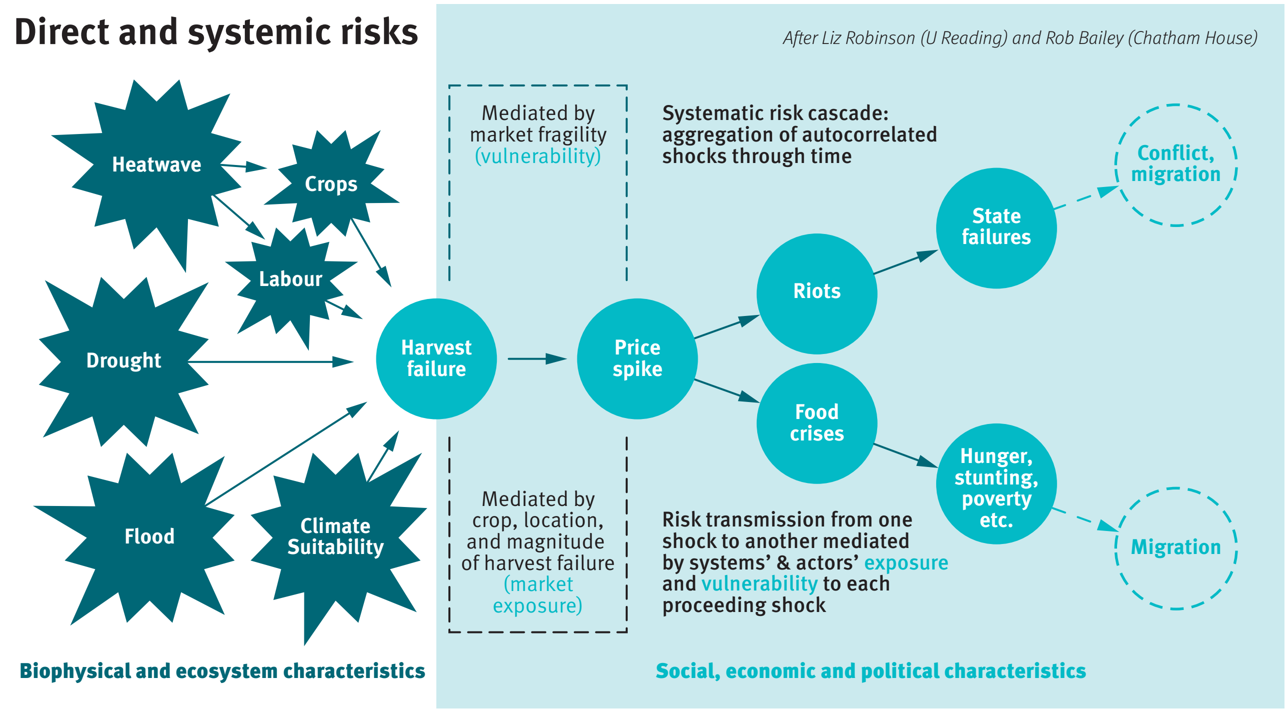


Figure 2: The link between direct and systemic risks: an example (developed from Robinson et al., 2018).

respectively by emissions or forcing scenarios (such as scenarios based on assumptions about the implementation of national COP climate pledges), ensembles of global climate models (for example the CMIP6 ScenarioMIP ensemble: O'Neill et al., 2016), and socio-economic scenarios (for example the SSP Shared Socioeconomic Pathways; O'Neill et al., 2015). These assumed drivers of change are then translated into direct risks using impact models. There are a number of major methodological challenges here, including (i) constructing climate projections for scenarios that have not been used directly to run climate models[3], (ii) constructing impacts models for all relevant dimensions of impact, and (iii) characterising uncertainty. Consequently there have been very few consistent multi-sectoral assessments of change in direct risk over the global domain (but see Arnell et al., 2019), particularly under policy-relevant emissions scenarios (see Gambhir et al., 2021 for an exception).

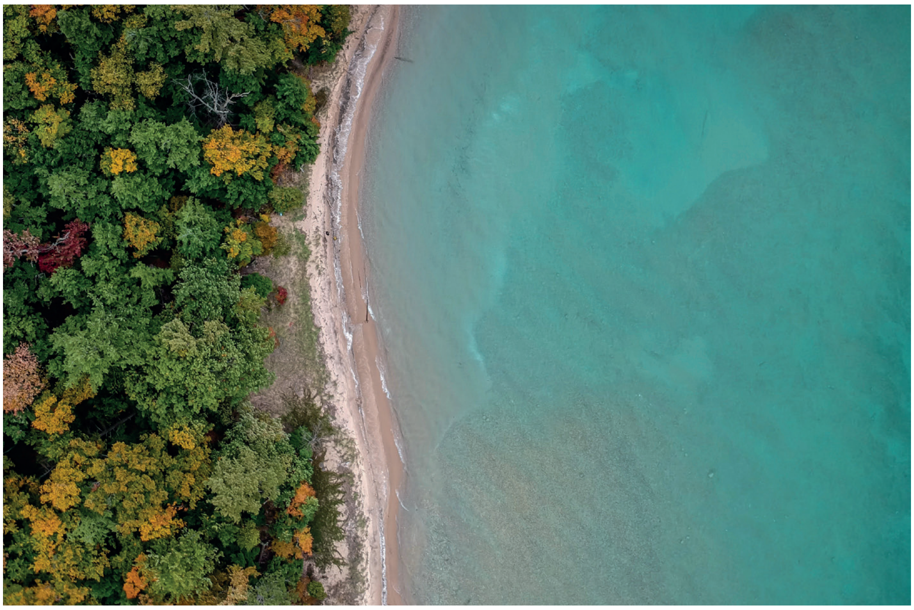
One particular gap is in the characterisation of the effects of ecosystem changes caused by climate change on impacts relevant to human systems (Martin-Ortega et al., 2021). Ecosystems provide provisioning, supporting, regulating and cultural services (Millennium Ecosystem Assessment, 1995) directly affecting the livelihoods of billions of people (IBPES, 2019) and indirectly affecting everybody. Ecosystems are defined by interactions among and between biotic and abiotic components, and are themselves vulnerable to systemic risks in the sense that impacts on one specific component have the potential to affect an ecosystem as a whole. Changes in just a few key species could potentially impact whole ecosystems, due to the linkages across ecosystem networks (Gilljam et al., 2015; Valiente-Banuet et al., 2015; Strona & Lafferty, 2016; Harley et al., 2017; Strona & Bradshaw, 2018).

The next section therefore summarises how ecosystem changes triggered by climate change might affect direct and systemic risks, and the following section discusses potential indicators which could be calculated.

[3] *Complex global climate models have typically been run with scenarios for future emissions that do not necessarily correspond well to current forecasts of where emissions are heading*

4. ECOSYSTEM DRIVERS OF DIRECT AND SYSTEMIC RISKS

Physical drivers of direct and systemic risk include heatwaves (terrestrial and marine), droughts, floods, fire, storms, and chronic changes in agricultural suitability.



These also affect terrestrial and marine ecosystems, which in turn have the potential to generate direct and systemic risks to human systems. The 'collapsology' literature (e.g. Diamond, 2005) is replete with – often controversial (Butzer, 2012; Richards et al., 2021) – examples from the past. We are taking an explicitly anthropocentric approach here, interpreting ecosystems explicitly in terms of their effect on human economic and social systems. It is recognised that ecosystems also have intrinsic value in themselves which humans have an ethical obligation to conserve (as specified in the preamble to the Convention on Biological Diversity).

It is possible to identify ten potential adverse consequences of ecosystem change which might potentially translate into direct and systemic risks (building on Oliver et al., 2021). These are summarised in Table 1, which also describes them in terms of ecosystem services. All may be driven by climate change now and in the future, but are superimposed onto the effects of other human pressures such as past and future land use change and the exploitation of habitats. These have been the dominant drivers of ecosystem degradation to date (IPBES, 2019), but climate change is projected to become as important within a few decades (Pereira et al., 2020; Newbold, 2018).

Resource depletion describes a reduction in the food, fibre and medicines that are provided through ecosystems, from both terrestrial and marine environments, and the consequences include long-term reductions and short-term disruptions to supply. The literature is large (see for example Brauman et al., 2019 for a review) with many local examples. In principle resource depletion includes managed agriculture, although changes in crop productivity is typically conceived as a direct impact of climate change rather than an ecosystem impact. A **loss of genetic resources** describes a reduction in genetic diversity due to population decline and species extinction which underpins the productivity and resilience of all ecosystem services including agriculture (Stratanovitch & Semenov, 2015; Khoury et al., 2021) and provides a reservoir for the discovery of potentially useful new medicines. A **decline in soil quality** is a reduction in soil nutrients, organic matter content and microbial and invertebrate communities, leading to a reduction in productivity and soil stability. The **loss of pollinators and natural predators of pests** describes a reduction in the abundance and diversity of pollinators and/or their temporal overlap with flowering (e.g. Kudo & Cooper, 2019) which is fundamental to the productivity of many crops, and reduction in beneficial insect predators of crop pests. The **emergence and expansion of plant and zoonotic diseases** describes the potential for new diseases to emerge following, for example, habitat encroachment, and the potential for current diseases (typically vector-borne) to expand their range. **Alteration of hydrological regimes** due to land cover change potentially affects the availability and quality of water resources, and removal of vegetation cover can also lead

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Table 1: Adverse consequences of ecosystem change

(non-exhaustive list: the drivers in italics are not considered further here)

Adverse consequence	Type of ecosystem service
Resource depletion	Provisioning
Loss of genetic resources	Provisioning
Decline in soil quality	Supporting
Loss of pollinators and predators	Regulating
Expansion and emergence of zoonotic and plant diseases	Regulating
Alteration of hydrological regime	Regulating
Reduced protection against natural hazards	Regulating
Loss of iconic or culturally important landscapes	Cultural
Alteration of global carbon budgets	*Regulating*
Alteration of local climate	*Regulating*

to **reduced protection against natural hazards** from landslides, erosion and flooding. With the exception of the loss of genetic resources, all these ecosystem changes could plausibly lead to direct and potentially systemic impacts on human systems.

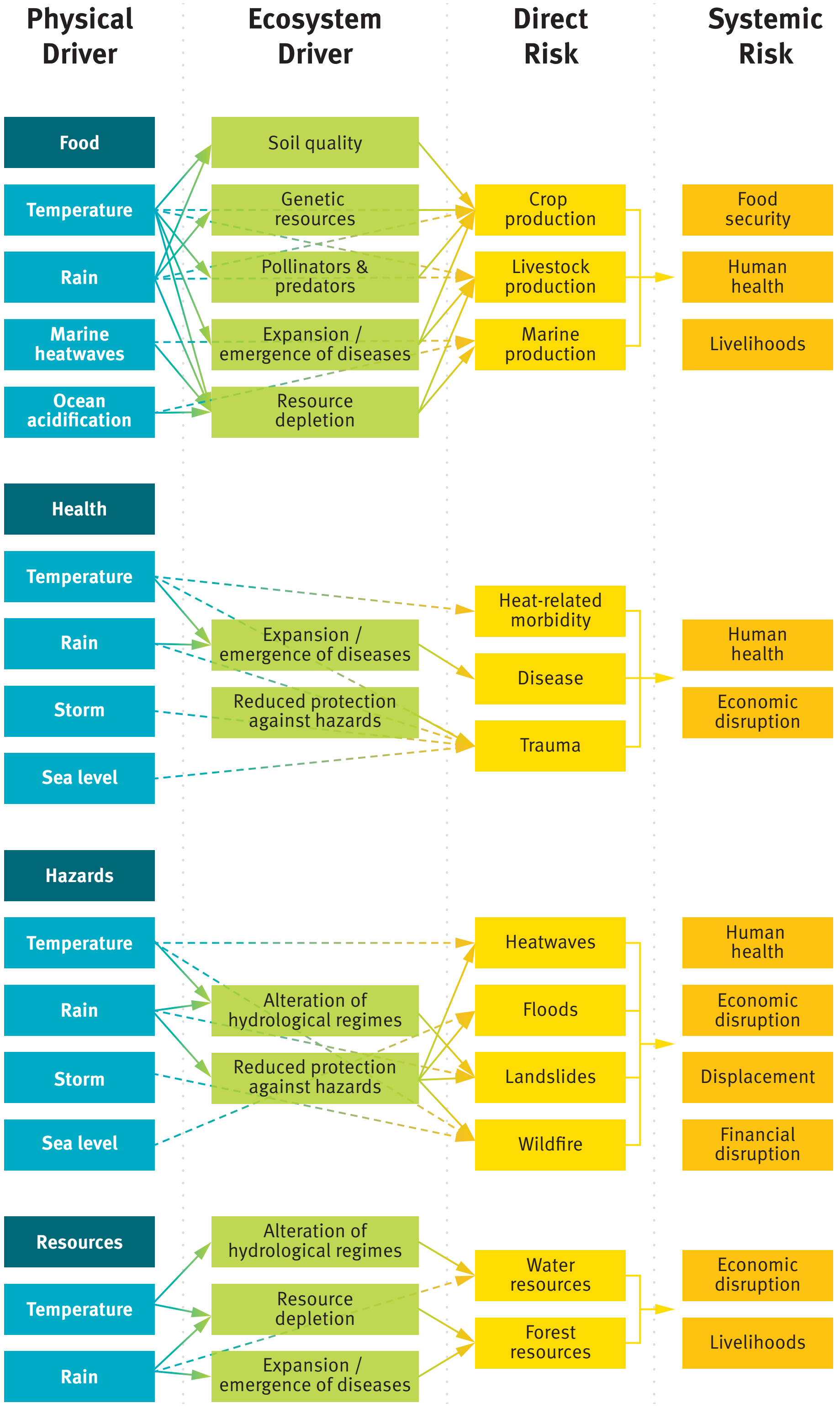
The loss of genetic resources represents a more indirect effect through increasing vulnerability to disease risk and extreme weather hazards, as well as representing an opportunity cost for loss of future medicines and resources.

A loss of iconic or culturally-significant landscapes represents a loss which impacts upon spiritual and religious values, aesthetic values or the opportunities for recreation and tourism: whilst this may be important locally, it is unlikely to generate major systemic risks at regional or global scales, but a reduced sense of connection to nature could affect attitudes towards the protection of nature (Oliver et al., 2022).

The last two adverse consequences listed in Table 1 describe potential **effects on local climate** of land cover change (through changing the local albedo or water balance) and potential **effects on the global carbon cycle** (through altering carbon sequestration). These two consequences are not considered further here, because their effects on human systems would be manifest through additional changes to the direct impacts of change in weather and climate (and effects are to a certain extent already incorporated in current climate models) – but they represent very important additional drivers of systemic risk by creating potential tipping points in the earth system (Lenton et al., 2019).

Figure 3 summarises potential pathways between direct physical consequences of climate change, the direct impacts and potential links to systemic risk domains, highlighting the effect of ecosystem changes (Table 1) driven by climate change on the direct impacts: the physical drivers (changes in weather and climate) affect the direct risks directly and through changes to ecosystems. It is important to emphasise at the outset again that ecosystem changes will also be driven by other factors including land use change and resource exploitation, and that the translation from direct to systemic risk depends on exposure and vulnerability (Figure 2). The figure focuses on four broad areas of climate impact. The four overlap and can be seen as different ways of looking at the challenge of climate change (for example it is possible to look through the lens of health, which includes the effects of changing hazards, or look through the lens of hazards, which includes the effects on health). There are other areas of impact or ways of looking at impact, but these are not so obviously potentially affected by

Figure 3: Overview of the effects of physical drivers and ecosystem changes on direct and systemic risks, for four areas



ecosystem changes (for example infrastructure reliability).

Changes in weather and climate have well-understood – though often quantified only with considerable uncertainty - direct effects on crop, livestock and marine production, through a wide range of mechanisms. Crop production[4], for example, will be affected directly by changes in agro-climatic suitability (for both crops and pests), reductions in time to maturity, the occurrence of heat extremes and changes in availability of water (and also the concentration of CO2 in the atmosphere which potentially increase growth of some plants), and higher temperatures may also affect the ability of farmworkers. Indirectly, climate change may affect the numbers of pollinators and natural predators (Settele et al., 2016), pests and diseases through changes in phenology and timing, and affects soil quality and health through altering organic matter content, soil structure and biome, and stimulating erosion. Livestock production will be directly affected by changes in the availability of water and by heat stress and indirectly affected through changes to the availability of food and fodder (ecosystem productivity) and increased occurrence of pests and diseases. Marine production (fish and shellfish) will be directly affected by marine heatwaves and ocean acidification, and indirectly affected through changes to the ecosystems that support fisheries caused, for example, by eutrophication and coral bleaching.

From a human health perspective, climate change has the potential to generate systemic public health and economic disruption risks through increasing

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heat-related morbidity and mortality (including the capacity to undertake labour), increased prevalence of disease and increased death and injury during extreme events. Heat-related ill-health is directly influenced by weather and climate. The expansion and emergence of disease, however, will be largely determined by the effects of climate change on the distribution of vectors over space and time (for example malarial mosquitoes) and the ecosystem interactions between hosts, vectors, pathogens and humans (Lawler et al., 2021).

From a hazard perspective, change in risk is driven by changes in the occurrence of extreme weather events, but the effects of these events may be strongly influenced – exaggerated or reduced – by changes in vegetation cover (Sudmeier-Rieux et al., 2021). Vegetation cover influences the effect of coastal storm surges, affects the chance of landslides and wildfire and the effect of heatwaves, and also affects river flood risk (primarily for relatively small floods).

From a resources perspective, changes to catchment vegetation cover affect the amount, timing and quality of water available to users, but the detailed effects depend on the type of vegetation change. Changes in ecosystem structure and the occurrence of pests and diseases affect forest resources.

Figure 3 provides a high-level overview of how the physical effects of climate change combine with indirect effects on ecosystems to affect direct risks which therefore potentially cascade on to systemic risks. The relationships are complicated, and – depending on the specific scenario or pathway - some of the links will be much more important in practice than others. The academic literature on these potential drivers of direct risk is diverse, uses a wide range of approaches and scenarios, is usually localised, and there are many major gaps. However, it is possible to draw four broad conclusions about how the consequences for impacts of changes to ecosystems caused by climate change might be different to the direct effects of changes in weather and climate.

First, most of the physical effects of climate change will manifest themselves through changes to the frequency, magnitude or duration of acute events – with the major exception of long-term chronic changes in climatic suitability for crops. In contrast, most of the effects of ecosystem change will manifest as chronic changes – perhaps becoming significant when some critical threshold is crossed – or will exaggerate or ameliorate the adverse consequences of acute physical events.

Second, ecosystem changes are sometimes irreversible (Scheffer et al., 2001)[5] whilst most of the direct physical drivers of impact are related to the magnitude of change in climate at a particular point in time: the major exception here is sea level rise, which depends on accumulated increase in temperature over time. This has important implications for impacts under emissions pathways which overshoot temperature targets and for long term commitments to change.

Third, ecosystems are by definition made up of interconnected parts, so estimating the effects of climate change involves an understanding of both how individual components are affected and how the characteristics of the system generate changes in the dimensions relevant to humans. This is essentially a systemic risk problem, and therefore very dependent on local context and circumstances.

Fourth, the geographic location of ecosystem changes is likely to be much more important than the geographic distribution of physical changes. The impacts of an increase in temperature on ill-health, for example, will vary across space with (i) exposed population and (ii) the vulnerability of that population to extreme heat (as reflected for example in varying critical temperature thresholds used in heatwave warnings), but in principle anywhere could be affected. In contrast, ecosystem changes that have the potential to generate regional and global systemic risks are likely to be concentrated in specific locations[6]. These are not necessarily where the changes are greatest, but where the changes are most likely to have large-scale consequences depending on the state (in terms of resistance and resilience) of the system affected. Vector-borne diseases, for example, tend to be geographically restricted, and the effects of habitat loss or encroachment may be particularly important in specific locations which are reservoirs for potential new diseases.

[4] *Note that crop production could be interpreted as an ecosystem service in itself*

[5] *Although conceptually it is possible for a system that replaces one that is lost provides more services to humans*

[6] *Note that these are not necessarily the frequently-cited 'biodiversity hotspots' (Myers et al., 2000) which are defined in terms of biodiversity rather than ecosystem services*

5. INDICATORS OF ECOSYSTEM CHANGE RELEVANT TO DIRECT AND SYSTEMIC RISKS

The previous section summarised how changes to ecosystems add to the direct physical drivers of climate impacts to create adverse consequences for human societies and potentially generate systemic risks.

In principle it is possible to estimate impacts in human terms (such as numbers of people affected), but in practice this is sensitive not only to climate and socio-economic change, but also to how resources and hazards are managed and adaptation decisions made by a large number of actors. For example, an estimate of the effects of a given climate scenario at a place on the numbers of people flooded would have to take into account local flood management practices and how these practices change over time. Impacts on crop production would depend on local farmer practices, farmer-scale adaptation, and changes to national and international crop markets. In practice, therefore, the potential direct impacts of climate change are typically characterised using indicators – for example change in the frequency of a specific return period flood, or change in the time taken for crops to reach maturity.

There have been a number of studies at the global scale which have produced indicators of the effect of these direct physical drivers, such as indicators characterising the frequency of heat extremes, droughts or flood impacts (e.g. Arnell et al., 2019). However, whilst a number of studies have assessed potential climate change impacts on ecosystems at global or local scales, these have generally been expressed in indicators relevant to ecosystems in themselves rather than ecosystem services or their consequences for humans. Mandle et al. (2021) noted that 'ecosystem conditions or processes along are rarely proxies for ecosystem service delivery'. Many have also concentrated specifically on indicators of biodiversity, interpreted as the sum of variation among and within species: this is only one dimension of an ecosystem. Predicted impacts can vary widely even among projections of the same component of biodiversity (Bellard et al., 2012), due to the complexities in ecosystems.

> ***The potential direct impacts of climate change are typically characterised using indicators – for example change in the frequency of a specific return period flood***
>
> ”

As outlined in Section 2, the focus here is on systemic risks with regional and global consequences, and these may be generated either by global-scale changes or changes in critical locations.

Table 2 gives some example indicators for the adverse ecosystem changes shown in Table 1, which have been calculated

Table 2: Global-scale indicators of adverse ecosystem change

Useful proxy indicators in italics

Adverse change	Indicator	Example reference
Resource depletion (pasture)	Net primary productivity Herbaceous biomass Grazing intensity	Boone et al. (2018) Godde et al. (2020) Fetzel et al. (2017)
Resource depletion (marine)	Fish biomass Fish range *Ocean acidification* *Extent of coral bleaching*	Free et al. (2019)
Loss of genetic resources		
Decline in soil quality	Soil organic carbon Soil erosion	Boone et al. (2018) Borrelli et al. (2020)
Loss of pollinators/predators	Specialist species' population characteristics	Dakos & Bascompte (2014)
Expansion / emergence of diseases	Mosquito range	Caminade et al. (2014); Campbell et al. (2015); Kraemer et al. (2019); Ryan et al. (2019;2021)
	Parasite prevalence	Cohen et al. (2020)
Alteration of hydrological regimes	Land cover change – river runoff change	
Reduced protection against hazards	Land cover change Coastal mangrove extent	Santilan et al. (2020)

at the global scale under climate change projections. Coverage is variable. Several studies have developed and applied models to estimate productivity of pasture, and there are models to estimate changes in marine fish biomass and range. Global estimates of change in soil organic carbon, as a proxy for change in soil quality, have been made using a range of models. Several studies have developed and applied statistical and mechanistic models to describe changes in mosquito range (relevant to a range of diseases), although there can be large differences between models depending on how they are formulated and the extent to which they incorporate human influences on dispersion. Change in land cover (most importantly forest to grass) has been simulated by several dynamic global vegetation models.

However, there are clearly many gaps in the availability of directly-relevant indicators across the global domain: estimates of the loss of genetic resources tend to be restricted to domesticated livestock, data on the loss of pollinators or predators is localised and patchy, and the indicators for expansion and emergence of disease focus on a small subset of vectors. For some indicators it may not be feasible or appropriate to attempt to calculate indicators at the global scale: for example, the pollinators relevant for different types of economically-important crops are region-specific.

One way of addressing these gaps is to use indicators developed at the global scale for a higher-level characterisation of ecosystems. There are three high-level ecosystem characteristics: ecosystem productivity, ecosystem form and structure, and habitat or ecosystem extent. These characteristics map onto the adverse ecosystem changes as shown in Figure 2. Ecosystem productivity can be represented by biomass or net primary productivity, either for an ecosystem (at a place) as a whole or for different biomes or trophic levels at a place. Ecosystem form and structure describes the composition and relationships

Table 3: Global-scale indicators of change to ecosystem characteristics

Ecosystem characteristic	Indicator	Example reference
Ecosystem productivity	NPP by biome type	Warszawska et al. (2013)
	Biomass by trophic level	Lotze et al. (2019)
Ecosystem structure	Species at risk of extinction	Warren et al. (2018)
	Gamma metric as indicator of change	Ostberg et al. (2015; 2018)
	Ecosystem collapse indicators	Obura et al. (2022)
Habitat extent and species range	Biome extent	Warszawska et al. (2013)
	Mosquito range	Caminade et al. (2014); Campbell et al. (2015); Kraemer et al. (2019); Ryan et al. (2019;2021)
	Parasite prevalence	Cohen et al. (2020)
	Fraction of species remaining	Nunez et al. (2019)
	Fraction of remaining area	Nunez et al. (2019)

within an ecosystem at a place, including characterisations of biodiversity and measures of ecosystem resilience. Habitat extent and species range describe the geographical distribution of habitats or species. Table 3 gives examples of published global-scale indicators of these ecosystem characteristics (some of which map directly onto those shown in Table 2). Although there are more global scale studies, they are by necessity rather generalised in terms of, for example, numbers of biomes or species considered. There remains too very little quantitative global-scale information on potential changes to ecosystem form and structure, except as represented by proportions of species (by taxa) at risk of extinction.

There are considerably more studies using relevant indicators of adverse ecosystem change at the national and local scales. However, these are mostly based on combinations of observations and expert judgment to monitor past change and assess possible future changes, rather than quantitative models (there are some exceptions to this using mechanistic models (e.g. for fisheries (Free et al. 2019) and pollinator abundance (Gardner et al., 2020)). Also, the studies typically – and obviously correctly – use indicators that are relevant to local ecosystems. For example, the UK Biodiversity Indicators (Defra, 2021) are based on observations in the UK, and Oliver et al. (2015) describe observed trends in species directly relevant to ecosystem functions and services in Great Britain.

It is possible to draw three general conclusions from this review of potential indicators of adverse ecosystem change which could be projected into the future.

First, most quantitative studies which make projections into the future concentrate on indicators relevant to ecosystems in themselves, rather than in terms of their contribution to ecosystem services relevant to humans. There are some exceptions to this, relating specifically to changes in pasture and fishery productivity and changes to the distribution of some vector-borne diseases.

Second, the global-scale studies typically use very generalised indicators (such as total productivity, broad biome type or proportion of species at risk of extinction) which may be difficult to map onto specific adverse ecosystem changes, whilst local-scale studies use indicators relevant to local circumstances which may be difficult to generalise.

Third, there is a distinction between studies which combine observations with expert judgment to assess possible future changes in qualitative terms, and studies which use statistical, mechanistic or trait-based models to calculate quantitative indicators. Several intercomparisons have also highlighted large differences in projected change between different ecosystem models.

6. CONCLUSIONS AND IMPLICATIONS

There is an increasing concern over the global-scale systemic risks posed by climate change, but so far few robust assessments under plausible scenarios for future greenhouse gas emissions.

Such robust assessments need to be based on a blend of quantitative assessments of the direct impacts of climate change and qualitative assessments of the effect of exposure and vulnerability on how systems react to change. There is, however, a lack of robust evidence for a significant part of this blend: the extent to which the effects of climate change on ecosystem services generate direct impacts on human systems and contribute to systemic risks. The effects of changes in ecosystem services are potentially different to the more direct impacts of change in weather and sea level for a number of reasons. Ecosystem changes are most likely to be chronic and irreversible, so the rate of change in climate is important and impacts are unlikely to be reversed if temperatures reduce after an overshoot. Ecosystem changes will be very dependent on local context – because ecosystems are inherently complex networks – and global-scale systemic risks are likely to be generated by localised impacts in particular places.

There are several reasons why there is a lack of quantitative information on how ecosystems might change in the future and how these changes might generate direct and systemic risks. 'Ecosystems' are difficult to define, and different characteristics

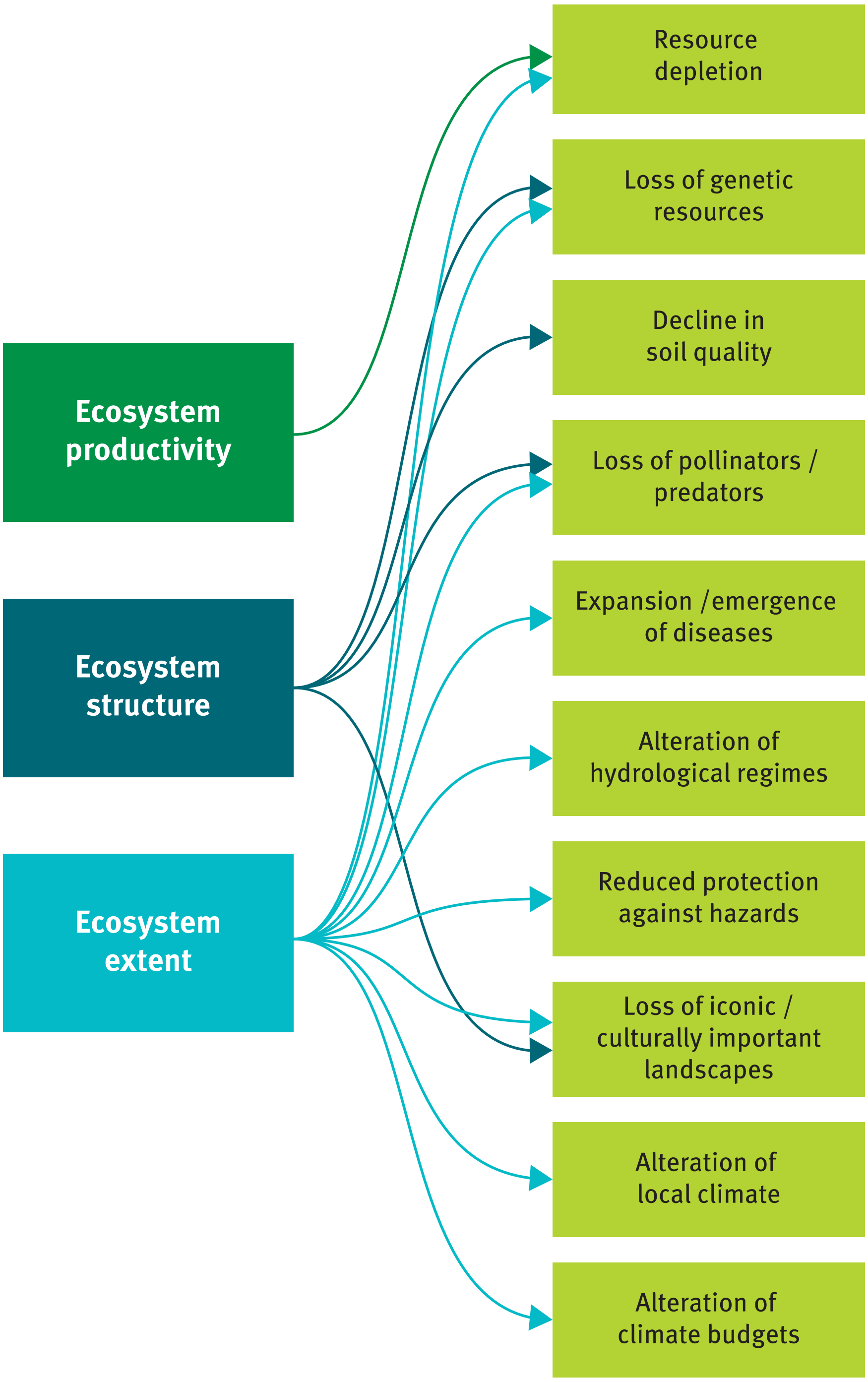

Figure 4: Relationship between ecosystem characteristics (left) and adverse consequences of climate change (right)

of ecosystems are relevant to human society in different places. They are difficult to model, with different models or types of models potentially giving different indicators of how ecosystems respond to change. Ecosystems are based on relationships, so estimating changes in features of the system as a whole involves understanding not only how individual components might change, but how relationships between components affect overall system change: ecosystems are exposed to systemic risk. Many studies focus on indicators relevant to ecosystems in themselves, rather than the services they provide to humans. Many studies are based on observations, for indicators that are challenging to model into the future. Finally, many studies focus on local consequences and global-scale studies have to rely on rather generalised indicators with looser connections to direct human impacts.

Regional and global systemic risks due to the impacts of climate change on ecosystems can arise either through impacts occurring over large areas, or through impacts occurring in specific locations that have larger-scale consequences. In order to undertake robust blended assessments of the effect of climate change on regional and global systemic risks which take account of the potentially-significant effects of changes to ecosystems, it is therefore necessary to incorporate information on ecosystem changes in two ways. The first is to use global-domain quantitative indicators where they can be calculated, combined with expert judgment on how these translate into terms relevant to human systems. The review presented here suggests that the expert judgment component will be vital, given that the global-scale indicators are rather high-level. The second, complementary, approach is to identify potential locations for ecosystem impacts that are directly relevant to human systems and regional and global systemic risks, and then use locally-relevant indicators to assess the effect of climate and other changes. In a sense, a blended expert-based assessment of the effects of ecosystem changes has to be nested in the blended expert-based assessment of the potential for climate change to generate systemic risks.

> ***The effects of changes in ecosystem services are potentially different to the more direct impacts of change in weather and sea level***
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