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A conceptual framework for cross-border impacts of climate change

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ABSTRACT

Climate change impacts, adaptation and vulnerability studies tend to confine their attention to impacts and responses within the same geographical region. However, this approach ignores cross-border climate change impacts that occur remotely from the location of their initial impact and that may severely disrupt societies and livelihoods. We propose a conceptual framework and accompanying nomenclature for describing and analysing such cross-border impacts. The conceptual framework distinguishes an initial impact that is caused by a climate trigger within a specific region. Downstream consequences of that impact propagate through an impact transmission system while adaptation responses to deal with the impact propagate through a response transmission system. A key to understanding cross-border impacts and responses is a recognition of different types of climate triggers, categories of cross-border impacts, the scales and dynamics of impact transmission, the targets and dynamics of responses and the socio-economic and environmental context that also encompasses factors and processes unrelated to climate change. These insights can then provide a basis for identifying relevant causal relationships. We apply the framework to the floods that affected industrial production in Thailand in 2011, and to projected Arctic sea ice decline, and demonstrate that the framework can usefully capture the complex system dynamics of cross-border climate impacts. It also provides a useful mechanism to identify and understand adaptation strategies and their potential consequences in the wider context of resilience planning. The cross-border dimensions of climate impacts could become increasingly important as climate changes intensify. We conclude that our framework will allow for these to be properly accounted for, help to identify new areas of empirical and model-based research and thereby support climate risk management.

1. Introduction

In 2011 Thailand experienced the longest duration flooding event in its recorded history (158 days), resulting in more than 800 deaths and affecting 13.6 million people in the country itself (Promchote et al., 2016). Devastating as these floods were for Thailand, the impacts beyond its borders were equally notable. The Bangkok region is home to large industrial parks that host numerous high value manufacturing concerns, many also located close to coastal port facilities to reduce transportation costs. Seven parks were badly affected, leading to enormous losses in the automobile and electronics industries (primarily Japanese companies), due to inundation of plants supplying key components to manufacturers in Thailand, throughout Asia and beyond. The implications of these severe inundation events at critical nodes in highly inter-connected global supply chains led to impacts that propagated far beyond the borders of Thailand. For example, ripple effects on the global economy were estimated to have reduced Japan's fourth quarter 2011 manufacturing production index by 2.4% (UN-ESCAP, 2012). The causes of the disastrous flood impacts are multi-faceted, but point to an imperative to build enhanced resilience into those components where impacts were propagated. However, superimposed on all of these immediate challenges is the spectre of a changing climate and associated

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sea-level rise, with the expectation of more frequent and severe events of this kind occurring in the future (Promchote et al., 2016). This example points more generally to the need for research on analogous cross-border climate change impacts and for their urgent consideration in adaptation planning.

Cross-border climate change impacts can be defined as consequences of climate change that occur remotely from the location of their initial impact, where both impacts, and potentially also responses to those impacts such as adaptation, are transmitted across one or more borders. The potential consequence therefore constitutes *a risk in a region of interest that is remote from the location of the initial impact*. The borders may be political (e.g., between countries or country groups), administrative (e.g., between sub-national jurisdictions), or "teleconnected" via more remote links (Benzie et al., 2019). Conventional climate change impacts, adaptation and vulnerability studies, including national risk assessments, tend to confine their attention to impacts and responses within the same geographical region (Fig. 1). It has been argued that this may expose major blind spots concerning the interactions and amplifications of impacts and their international dimensions (Challinor et al., 2017).

In this paper we propose a conceptual framework and accompanying nomenclature for describing and analysing cross-border climate change impacts. One difficulty faced in attempting this, is that research into cross-border impacts is dispersed and fragmented, often being addressed within different contexts or classified under contrasting headings. For example, in the regional impact chapters of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report "cross-regional phenomena" are referred to, which include impacts of climate change on international trade, on financial flows and on human migration and transboundary ecosystems (Hewitson et al., 2014). However, the detailed description of these impacts is dispersed across thematic chapters of the report.

The limited work that has considered cross-border impacts to date all suggests that these impacts can be non-trivial, meriting more detailed attention. It includes a number of national risk assessments in Europe, such as for the UK, Switzerland, the Netherlands and Finland, which have been summarised by Benzie et al. (2019), and for the United States (Smith et al., 2018), Norway (Prytz et al., 2018) and Germany (Peter et al., 2021). The studies highlighted potential impacts of increases in adverse climate events on trade, businesses and supply chains and the political and security implications of impacts on partner countries, requiring intervention in terms of development assistance, diplomacy and foreign policy. One study for the UK, for example, concluded that cross-border impacts on trade, investment and supply chains for food could be an order of magnitude larger than domestic impacts (PwC, 2013).

Other studies include emerging work on climate change risks in global supply chains (Ghadge et al., 2020), on transboundary water stress (Munia et al., 2020) and on trade implications of heat-related labour productivity losses (Knittel et al., 2020), some sector-based economic studies (e.g., impacts of weather shocks on the world food system – Janssens et al., 2020; Gaupp et al., 2020) and selective vulnerability mapping exercises (Hedlund et al., 2018). The European Environment Agency also draws attention to the phenomenon as part of a larger assessment of climate change impacts and vulnerability in Europe (Lung et al., 2017).

The importance of cross-border links has also been stressed in other fields of research. For instance, networks of cross-border financial exposures have been highlighted that can contribute to the propagation of impacts across otherwise remote geographical regions (e.g., Bricco and Xu, 2019; Aldasoro et al., 2020; ECB, 2020).

Why, then, focus on the risks resulting from cross-border climate change impacts specifically? The main reason is that climate change has developed into an important scientific and policy field in its own right. As a result there is a need for structure and clarity to identify the mechanisms via which climate change creates risks for society (see Simpson et al., 2021 for a detailed framing of this). Knowledge on climate change impacts, adaptation and vulnerability is synthesised by the IPCC Working Group II and is meant to inform existing policy processes that aim to facilitate adaptation including those coordinated at the international scale by the United Nations Framework Convention on Climate Change (UNFCCC) including the National Adaptation Plans process. These processes have been criticised for adopting an overly territorial or geographically bounded view of climate change impacts and adaptation (see Liverman, 2016; Magnan and Ribera, 2016; Benzie and Persson, 2019). Therefore, there is a need to raise awareness of the importance of cross-border climate change impacts within the existing scientific and policy realms that already work on addressing the problem of climate change; this is a primary objective of the conceptual framework presented below.

Previous studies have also attempted to address this problem. For example Moser and Hart (2015), invoking the concept of societal teleconnections, suggest a framework that describes the processes, structures and substances that connect different locations ("here" and "there") that will be impacted by climate change. Subsequently,

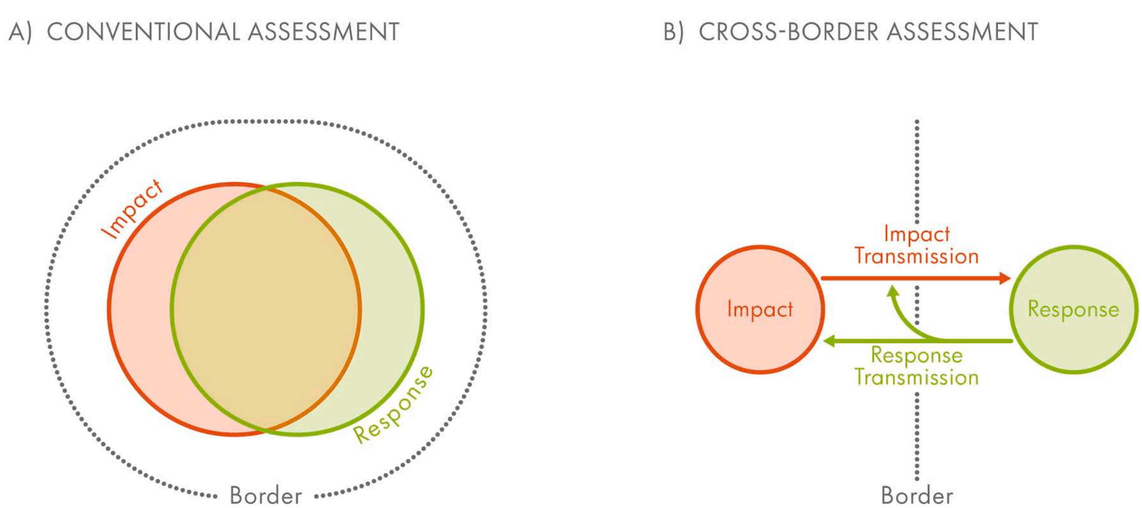

Fig. 1. Relationship between an impact and a response: a) in conventional climate change impacts, adaptation and vulnerability (IAV) assessments, where the impact and response to that impact lie within the same region; b) in cross-border IAV assessments, where impacts and responses (i.e., adaptations) are located in two regions separated by a border (e.g., political or administrative), with impacts transmitted between the regions (red arrow) and possible ameliorative responses transmitted back towards the impacts (green arrows).

Challinor et al. (2018) list international and domestic factors that will influence transboundary and trans-sector climate risk transmission. The framework we propose builds on these and other similar endeavours (e.g., Hedlund et al., 2018; Adaptation Without Borders, 2019; Gaupp, 2020), aiming first, to provide more detail on the elements that constitute and influence the cross-border transmission of climate change impacts and second, to achieve a more comprehensive and flexible framework for facilitating application to and comparison between cases from all sectors, scales and systems.

The relative neglect of cross-border impacts in national and international policy-making may increase potential risks and the costs of inaction. However, the design of actionable adaptation strategies to address such risks calls for a proper conceptualisation of the processes, scales and dynamics involved. Yet, whilst there are numerous methods and tools available to investigate selected dimensions of cross-border impacts, risks and responses, hitherto there has been no attempt to systematise these using consistent terminology (e.g., see discussion by Benzie et al., 2017) into a coherent methodological framework for designing scientific analyses and policy responses.

A conceptual framework can hence be useful for:

- *providing a nomenclature* or common language to describe structural elements of cross-border climate change impacts and their interactions;
- *enhancing understanding and raising awareness* by characterising and classifying the different elements involved (e.g., drivers, triggers, processes, dynamics and scales) to provide a systematic and transparent mapping of cross-border climate change impacts;
- *facilitating consistent comparison* of cross-border impacts in different sectors and geographies within a common framework, even if these may have been analysed across a range of disciplines that use contrasting data and methods with different degrees of complexity (e.g., compare cross-border impacts of flooding in the context of a transboundary river basin versus a global financial network);
- *informing adaptation planning*, by offering a structure both for exploring, identifying and assessing the risks and uncertainties resulting from cross-border climate change impacts and for targeting effective responses within the wider context of enhancing resilience.

In the following sections we first assemble the elements and nomenclature of a suggested framework. In Section 3 we introduce a selective typology of impacts and responses that can be used to characterise the elements of the framework. Section 4 demonstrates the framework using concrete examples – some already observed; others ongoing, anticipated or hypothetical. Section 5 discusses the potential utility of the framework for enhancing risk assessment and informing climate change adaptation planning, with some conclusions drawn in Section 6.

2. Framing cross-border impacts and responses

The framework focuses on how a climate impact occurring at a given location may be transmitted across borders, potentially presenting a risk to a region of interest that is remote from the initial impact, which may require a response from actors in that region. Implicit is an assumption of demonstrable or, if that is not feasible, of plausible causality in the relationships between linked elements of the framework. The elements are illustrated in Fig. 2.

It distinguishes first, a *climate trigger* that induces an *initial impact*, though other non-climatic triggers (e.g., economic, geophysical, health-related or geopolitical shocks) may precondition or exacerbate the impact. Hence, the impact is “initial” in the sense of being the system component first affected significantly by climate, serving as a point of departure for the research focus here. The climate trigger may be a short-period weather shock or slow onset event (see section 3.1). A central premise of the framework is that the frequency and/or

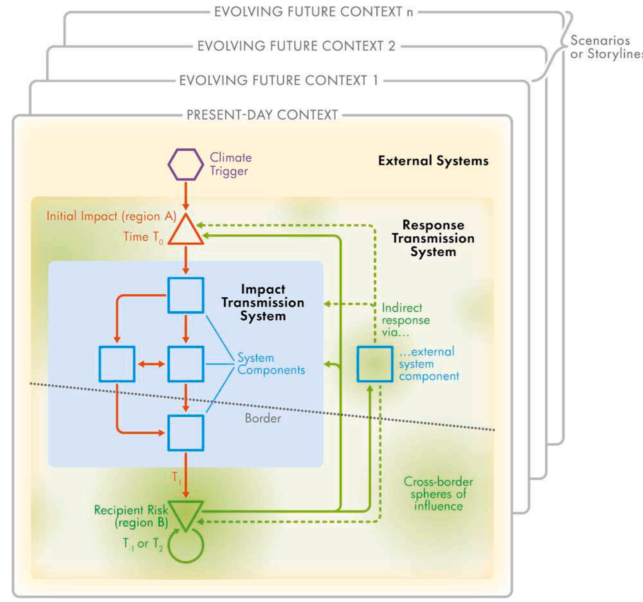

Fig. 2. Conceptual framework for the transmission of cross-border impacts and responses. An initial impact in one region due to a climate trigger is propagated (red arrows) via an impact transmission system (blue area) comprising impacts on interconnected system components of varied complexity, resulting in a recipient risk in a second region (location of the border is notional). Adaptive responses for ameliorating that risk (green arrows) can be targeted within a response transmission system (green area) directly at the recipient risk itself, at the impact transmission system and at the site of initial impact (solid arrows), and indirectly via system components external to the impact transmission system (dashed arrows). Responses can occur prior (T_{-1}) or subsequent (T_2) to the times of the initial impact (T_0) and recipient risk (T_1), to indicate anticipatory or reactive adaptation. The ability to respond can vary in terms of the sphere of influence exerted by the regional actor managing the recipient cross-border risk (strength of background green shading tone). Note that a response with longer-term effectiveness, operating directly on the climate trigger and not shown here, would be greenhouse gas mitigation. Transmission systems are shown in relation to external systems that may include non-climate drivers of key importance in understanding both the propagating impacts and necessary responses. The present-day context in which the systems operate is coloured yellow and evolves into an uncertain future, depicted as stacked scenarios or storylines.

magnitude of the climate trigger can be linked to and is liable to be altered by a changing climate. Hence the question of climate change attribution (e.g., Otto, 2016) is of importance in this context as well as attribution of the initial impact to a climate cause (Rosenzweig and Neofotis, 2013).

The initial impact of a climate trigger is felt in the region(s) in which the climate trigger operates. It may then have downstream consequences that can propagate across space (sometimes crossing borders) and through time (usually lagging behind the initial impact). We refer to this propagation of impacts as an *impact transmission system* and it can vary enormously in its direction and complexity (blue area in Fig. 2). Transmission mechanisms encompass various flows that might be physical (e.g., raw materials, commodities, manufactured goods), information (e.g., price, capital, data) or natural (e.g., ecosystem services, species).

The location of the border in Fig. 2 is merely notional, since cross-border impacts may occur across single or multiple borders that can be close to or more distant from the regional of interest. Impacts occurring at any point in the impact transmission system are themselves very likely to be subject to local responses of the type depicted in Fig. 1a. However, these are not shown in Fig. 2 as our focus is on the potential aggregate or net impact that may be transmitted into a region of interest. This we define as the *recipient risk*. Note that though the term risk suggests adverse impacts, opportunities may also arise from such impacts. The implication is that regardless of the types of impacts, they may require some kind of response or adaptation to offset damage or to exploit possible benefits. An understanding of the transmission of impacts can therefore help to inform responses for ameliorating the resulting recipient risk. We illustrate some initial impacts and their propagation in Section 3, below.

The options available for responding to the recipient risk by individual or multiple actors in the region of interest are illustrated in the green area of Fig. 2.

As the logical counterpart to the impact transmission system, we refer to these different types of response collectively as the *response transmission system.* These are responses, which may be reactive (at time T_2) or anticipatory (at time T_{-1}). Responses may involve interventions to mitigate the risk at the point of receipt (e.g., by altering exposure or vulnerability to the impacts actually or potentially received). They could also involve interventions that are directly targeted at one or more of the impacts being propagated in the impact transmission system and/or at the source of the initial impact. Then there are responses that may ameliorate the recipient risk indirectly, via a third party or external system component, for instance by influencing other actors to intervene in the impact transmission system or at the source of the initial impact or by spreading the recipient risk among additional systems. Another possible response (not shown) is to mitigate the causes of climate change, but outcomes would normally be manifest at longer time scales than these adaptation responses and while vital as a policy measure, they are not considered further here.

In a complex dynamic system, responses are also very likely to have unintended consequences. Change in one part of a dynamic system leads to changes in another part, and these consequent changes are not always controllable or foreseeable. It is therefore important that responses are framed in this systemic way so that it is possible to identify and analyse the ethical, political and self-interested rationales that might result in such unintended consequences (and see Simpson et al., 2021).

It is important to acknowledge that the ability of a regional actor to manage the recipient risk depends on the actor's *sphere of influence* with respect both to the impact transmission system and to the wider context in which the risks are generated (green shading in Fig. 2). This will likely be a gradient or continuum from "total control" to "no influence" and may change over time and in response to the climate impact. To take a commodity trading example, a country may exert more political and economic influence on a distant trading partner with which it has a long-standing trading relationship than it does on a nearby country managing the transit of commodities in a supply chain affected by a remote climate event.

In reality, multiple cross-border impacts are taking place in the wider context of an interconnected, globalised and evolving world (yellow rectangular area representing the present-day in Fig. 2). The impact transmission system and response transmission system that directly affect the recipient risk can be expected to interact with *external systems* that account for all other aspects of natural and societal processes. The environment and society are constantly evolving, which affects the context in which future risks due to cross-border impacts will occur. Uncertainties in the future context can be represented using alternative scenarios or storylines of environmental change (which influence the triggers of initial impacts) and of socio-economic development (which mediate impact propagation as well as potential interventions). Each alternative future is represented as a stacked uncoloured rectangle in Fig. 2. All future developments can be considered hypothetical, with some (e.g., those that imply a business as usual development) potentially serving as reference or "counterfactual" cases for testing the effectiveness of different adaptation measures.

3. Typologies of cross-border impacts and response

The conceptual framework illustrated in Fig. 2, of necessity, is a simplified representation of reality. The processes of cross-border impacts may materialise in many different ways, and it is important to understand these in order to design appropriate responses. It can also be helpful to characterise the separate elements and their assumed causal relationships for assisting in the deployment of suitable methods of assessment. Many of these elements are depicted in Fig. 3, which can be thought of as a toolbox from which components are selected according to a case in question, and inserted in the relevant part of the conceptual framework. However, it should also be understood that given the numerous variants and complexities of cross-border impacts, the examples shown in Fig. 3 are intended to be indicative and are by no means exhaustive.

3.1. *Types of climate trigger*

Two types of climate trigger are identified in Fig. 3a: weather shocks and slow onset events. The trigger may be a short-period *weather shock*, which could be an individual event (e.g., flood, storm, heatwave or drought), compound concurrent or consecutive event (e.g., coincident pluvial flood, storm surge and strong wind) or simultaneous "teleconnected" weather events at distant locations that are related to a single cause (e.g., floods and droughts in different regions due to El Niño conditions). Alternatively, the trigger may be a longer-period, *slow onset event*, such as a gradual increase in climate-related stress due to a slow change of climate across a critical threshold (e.g., shifting zones of crop suitability due to warming and drying that decreases productivity in core production areas).

3.2. *Categories of cross-border impacts*

The unique characteristic of cross-border climate change impacts represented in this conceptual framework is that the initial impact of climate occurs remotely from its final consequence and potential responses, and that both impacts and potentially also responses to those impacts are transmitted across one or more borders. There are various classifications of such impacts in the literature (e.g., see Benzie et al., 2016; Hildén et al., 2016; Lung et al., 2017) and seven categories are identified here (Fig. 3b), based on Benzie et al. (2019): ***trade*** (e.g., flows of commodities on international markets), ***finance*** (the movement or change in value of public and private capital), ***people*** (movement of people across borders, such as through migration and tourism), ***psychological*** (impacts brought about by actions of different actors and particularly the media, based on their perceptions and communication of cross-border risks and opportunities – referred to as a cognitive filter by Benzie et al., 2019), ***geopolitical*** (e.g., climate-related impacts on international relations, resource access and strategy), ***biophysical*** (e.g., water transfer among hydrological systems and movement of species, pests or pathogens) and ***infrastructure*** (e.g., transport and telecommunications links). Examples that each involve one or more of these are illustrated in Section 4, below.

3.3. *Impact transmission scales*

In Fig. 3c we have identified some of the scales at which impacts may be transmitted following an initial impact. Impact propagation from the initial impact to the recipient risk occurs across a border or borders that can be administrative, physical or societal. The scales of transmission may be characterised as:

- Across *neighbouring regions*: transmission between locations in adjacent geographical regions (e.g., transmission of floodwater in a shared river basin from one country to another).
- Between *remote regions*: transmission between locations distant from one another and separated by multiple borders (e.g., impacts of a supply shortfall of a traded food commodity affected by weather at one location and transmitted via higher prices in the global food

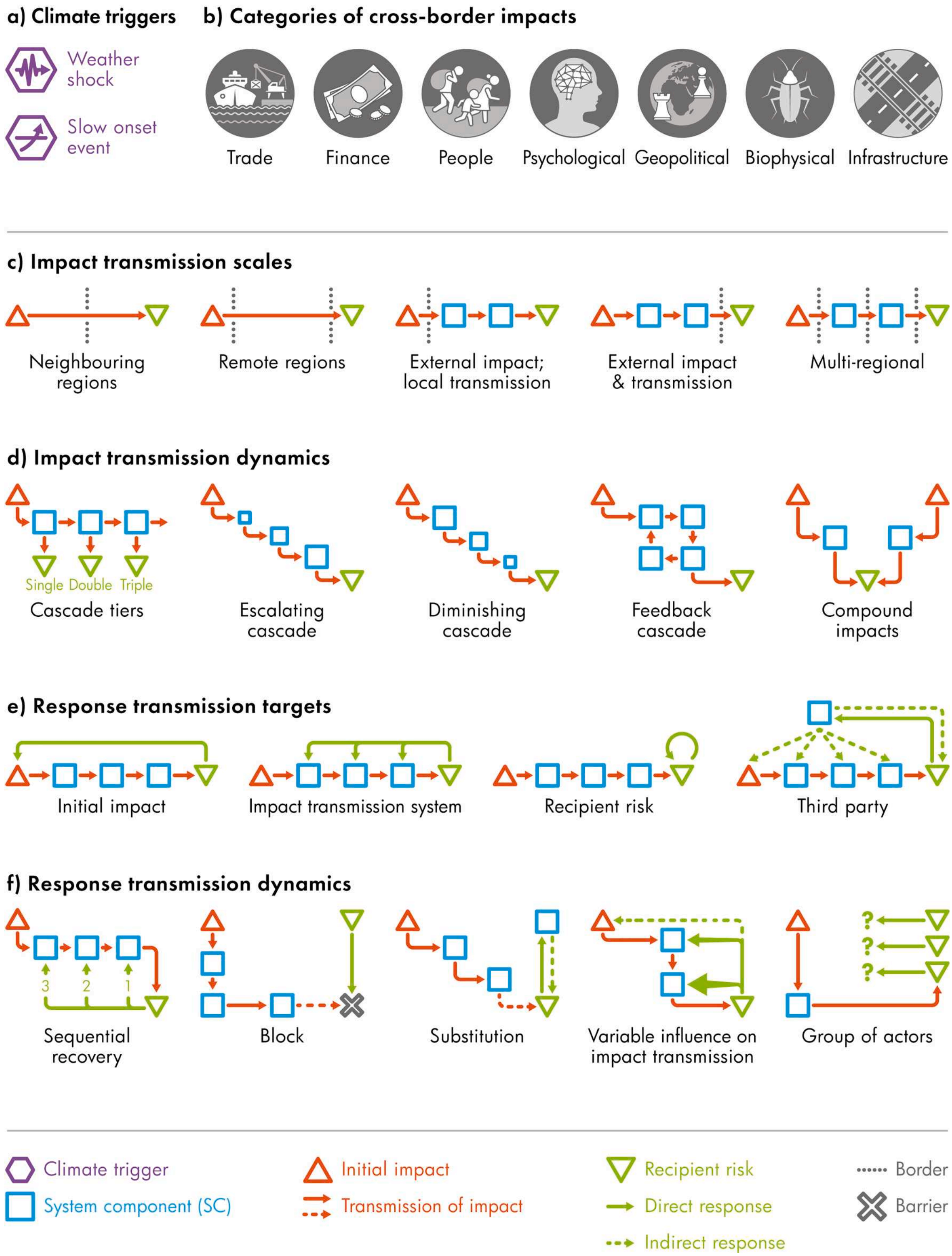

Fig. 3. Typologies for representing cross-border climate change impacts. Specific cases may treat one or more categories of cross-border impacts (b) characterised by types of climate triggers (a), impact transmission scales (c) and dynamics (d), and response transmission targets (e) and dynamics (f). These are indicative and not intended to be comprehensive. For explanation, see text.

trade system to regions dependent on its import but remote from the weather impact).

- *External impact; local transmission*: where the initial impact occurs in a jurisdiction external to the recipient risk, whereas all subsequent impacts are transmitted within the same, "local" jurisdiction as the recipient risk (e.g., storm damage at a major container port in Brazil may disrupt deliveries of commodities to a European port of entry such as Rotterdam, with subsequent cascading repercussions through supply chains across Europe).
- *External impact and transmission*: where the initial impact and all subsequent impacts are transmitted within a jurisdiction external to the recipient risk (e.g., losses to rice production between an Asian producer experiencing harvest failure, quality deterioration at on-site storage facilities and spillage during transportation to a

processing plant prior to manufacture of a food product, and then shipment to a European port of entry).

- *Multi-regional*: propagation of impacts involves transmission via system components located in more than one jurisdiction between the initial impact and recipient risk (e.g., drought affecting water availability, transfer and multi-purpose use in an international river system passing through several countries).

In fact, the above distinctions are somewhat blurred. For instance, the location of impact transmission in the third and fourth cases above might be regarded simply as nuanced variants of multi-regional scale transmission, Note also that though impacts are used to illustrate the scales of cross-border transmission in Fig. 3c, similar scale demarcations could also be envisaged for the transmission of responses (not shown).

3.4. Impact transmission dynamics

The transmission of impacts can take place in many different configurations, sometimes combining features of several of these. We illustrate six options in Fig. 3d.

- *Cascade tiers* describe a situation in which the propagation of an initial impact is transmitted through a cascade of impacts on system components. Impacts at each tier of the cascade are themselves associated with a recipient risk of concern, the extent of which may be influenced by other features of the transmission dynamics. For example, businesses handling materials at different 'stages' of a complex supply chain (e.g., export, processing, retail), with disruptions at each stage having knock-on consequences e.g., for profitability for each recipient group.
- An *escalating cascade* characterises cases in which impacts are being transmitted in a cascade from one system component to another, with each subsequent impact amplified compared to the previous one. For instance, this kind of situation can sometimes arise in supply chains following a climate-induced shortfall in a commodity, a rise in price that subsequently provokes an over-reaction such as panic buying, stockpiling or market intervention that drives up the price of the commodity even further than the original situation might have merited.
- A *diminishing cascade*, is the inverse of the escalating cascade, where each subsequent impact propagated in a cascade is dampened or reduced compared to the previous one. Using a similar supply chain example, fixed prices may be built-in to contracts between retailers and suppliers, hence safeguarding prices for recipient consumers but also implying that suppliers would absorb any additional costs (potentially exposing them to increased impacts).
- A *feedback cascade* refers to cases in which impacts propagating from one system component to another may actually feed back to earlier links of the cascade, hence adding complexity to the impact transmission and its influence on the recipient risk. For example, perishable food products affected by weather at a source location may suffer quality losses during transportation to manufacturing plants, resulting in requests for additional high quality produce from suppliers at points earlier in the supply chain.
- *Compound impacts* can be realised in different ways. The variant shown in Fig. 3d is where initial impacts occur concurrently at two different locations and are propagated through separate impact transmission systems before converging to affect the same recipient human or natural asset at risk. For example, a drought in one location affects the supply and price of hydroelectric power whilst a heatwave at another location affects the cooling capacity, supply and price for water-cooled nuclear power, with both sources contributing to the overall cost of electricity for a recipient consumer. Another variant might involve climate impacts of one type that may induce impacts of another type (e.g., a drought may predispose a region to crop failure, with implications for food security in a recipient region, but may also induce wildfires, leading to cross-border smoke pollution that can aggravate health problems in the same recipient region).

3.5. Response transmission targets

Responses designed to ameliorate the risk of cross-border impacts can be directed towards a number of possible sources of that risk (Fig. 3e). Responses may involve interventions that target:

- the *initial impact*, directed at the source of that impact (e.g., by offering assistance to repair damaged infrastructure at a key export hub following a catastrophic storm);
- the *impact transmission system*, through actions directed at one or more of its system components (e.g., by using diplomatic means to discourage market interventions by countries affected by a weather-related commodity shortage that might aggravate shortages elsewhere);
- the location of *recipient risk*, by reducing exposure or vulnerability of assets affected by the impacts and hence mitigating the risk at the point of receipt (e.g., reducing exposure to supply interruptions by increasing strategic reserves of a key commodity);
- a *third party*, where the risk is ameliorated indirectly via an external system component, for instance, by influencing other actors to intervene in the impact transmission system or at the source of the initial impact (e.g., encouraging other countries to provide assistance to repair damaged infrastructure) or by spreading the recipient risk among additional systems (e.g., see *substitution* in section 3.6, below).

Note also that responses may not be targeted exclusively to avoid or ameliorate adverse impacts. Some may be directed towards exploiting beneficial effects, for example to invest in additional storage and infrastructural capacity to account for growing crop productivity in exporting regions benefiting from a shift to more favourable climate.

3.6. Response transmission dynamics

The transmission of responses to ameliorate propagating impacts can be highly complex, with many potential impediments or amplifiers affecting the dynamics of transmission. A few examples that characterise this complexity include (Fig. 3f):

- *Sequential recovery*, where responses to impacts on individual system components along a chain of impacts may be intentionally staggered in time to target critical points of vulnerability over less crucial elements (e.g., to prioritise actions at a major choke point in a supply chain).
- *Block*, which refers to means for setting up barriers to prevent the cascading impacts from affecting the assets at risk (e.g., by putting in place effective screening mechanisms to inhibit the spread of crop pests via imported plants or seeds into regions that would potentially offer a new niche under a changed climate).
- *Substitution* describes the spreading of risk by opening an alternative channel for that risk via a third party or external system component (e.g., negotiating a new agreement with an alternative supplier of a key commodity).
- *Variable influence* on the impact transmission system, indicates how the ability to respond can vary according to the sphere of influence exerted by the regional actor managing the recipient risk (e.g., a country may exert more political and economic influence on a distant trading partner with which it has an historical trading relationship than it does on on a nearby country managing the transit of that commodity on purely commercial grounds).
- *Group of actors* refers to cases where climate impacts propagating through the same impact transmission system poses risks for different recipient actors, each of which organises responses either

individually or collectively. To illustrate, repatriation of citizens in response to severe hurricane damage in Caribbean tourist destinations visited by Europeans would ordinarily be organised separately by individual countries, whilst disaster relief for the source region might be coordinated at EU level.

3.7. Socio-economic and environmental context

Cross-border climate change impacts are influenced by the *larger-scale context* in which they occur at a given point in time (see Fig. 2). This context is commonly described by sets of driving factors that characterise the major controls on socio-economic and environmental conditions. These are indicators for which quantitative or qualitative information is available or might need to be gathered afresh, whether from statistics of past and new observations or from model projections or narrative conjectures (scenarios) of the future. A useful basis for selecting socioeconomic drivers in climate change assessment is provided by the shared socioeconomic pathways (SSPs), for which nine categories have been suggested as relevant for defining challenges to mitigation and adaptation (O'Neill et al., 2014): demographics, economic development, welfare, resources, institutions and governance, technological development, broader societal factors and policies and environmental and ecological factors. The last of these are typically characterised by climate model projections based on representative concentration pathways (RCPs) that describe alternative trajectories of future greenhouse gases and aerosols in the atmosphere (e.g., Ito et al., 2020), and hence link directly to the climate triggers (assuming appropriate attribution). Socioeconomic drivers influence society's exposure and vulnerability to climate that are integral in preconditioning the types of impacts set in train by a climate trigger. Importantly, many of the same factors, such as poverty, inequality, governance and education, also predispose society to impacts due to non-climate triggers. Hence, by framing cross-border climate impacts and their responses in a wider context, both the environmental and social dimensions of resilience (see Opdyke et al., 2017) can be enhanced across a range of potential risks. Finally, whilst most of these contextual drivers describe trends or period-averaged conditions, singular *wild card events* (not depicted in Fig. 3), such as wars, pandemics or major volcanic eruptions, can trigger effects that are often unexpected, acute and far-reaching and may interact with climate-related impacts.

4. Operationalising the framework

In order to explore the potential value of the conceptual framework,

Table 1
Six contrasting examples of cross-border impacts of climate change, comparing categories of impact, recipient regions at risk, time frame, type and attribution of climate trigger, scale and transmission dynamics of impacts and responses. Italicised entries refer to elements depicted in Fig. 3.

Impact example	Category of impact	Recipient regions of interest	Time frame	Climate trigger & attribution	Impact transmission		Response transmission targets/dynamics
					Scale	Dynamics	
Thailand 2011 flood damage[1,2]	*Trade; Finance; Infrastructure*	Japan EU (manufacturing supply chain risks)	Observed	*Weather shock* (flooding) Attributed[1]	*Multi-regional*	*Escalating cascade* (component supply choke points)[2]	*Substitution* (alternative suppliers); *Target recipient risk* (buffer stocks for recovery period)[2]
Norwegian & Swedish hydropower production[3]	*Infrastructure; Finance*	Finland (risk for capital intensive fossil & nuclear; opportunity for renewables)	Ongoing; Future	*Slow onset* (increasing precipitation)[4] Projected[5]	*Neighbouring regions*	*Single tier cascade* (increased generating capacity affecting the price of imported electricity)	*Substitution* (invest in renewables & smart demand management); *Group of actors* (power companies; grid operators)[3]
Argentine soymeal & soybean crop failure 2018[6]	*Trade*	EU & China (consumer risks) US, Paraguay & Brazil (producer benefits)	Observed	*Weather shock* (unusually severe drought)[7] Not attributed	*Multi-regional*[8]	*Single tier cascade* (transfer of costs along the supply chain) *Diminishing cascade* (initial soy price rises; Paraguay, US & Brazil alternative suppliers)	*Substitution* (opportunistic soy planting in Brazil & US; EU & China imports from US increase)[6]
Grand Ethiopian Renaissance Dam drought impacts[9]	*Biophysical; Geopolitical*	Sudan & Egypt (water security)	Future	*Weather shock* (drought)[10] Projected[11]	*Neighbouring regions*	*Double tier cascade* (water for irrigation and hydropower)[12,13]	*Group of actors* (legally binding international agreements on water release)[9]
Arctic sea ice decline impacts[14]	*Finance; Infrastructure; Trade; People; Geopolitical; Psychological*	EU (security, economic & environmental policy)	Ongoing; Future	*Slow onset* (warming & sea ice decline) Attributed[15]	*Multi-regional*	*Multiple tier cascade* (resource exploitation; trading routes; tourism; environmental impacts)[16,17]	*Group of actors* (security via diplomatic & military means; environmental protection); *Block* (access to ice-free sea routes)[14, 16-17]
Russian & Pakistan crop failures of 2010[18]	*Trade; Finance; Psychological*	United Kingdom (food affordability)	Observed	*Weather shock* (Russian drought & Pakistan flooding)[19,20] Attributed[21]	*Multi-regional*	*Compound impacts* (yield shortfall of staple crops in Russia & Pakistan): *Escalating cascade* (cereal yield decline; food price rise; export ban; panic buying)[18]	*Target recipient risk* (food banks in UK); *Target initial impacts* (food aid to Pakistan)[18]

[1] Promchote et al. (2016); [2] Haraguchi and Lall (2015); [3] Hilden et al. (2018); [4] Caloiero et al. (2018); [5] Rajczak and Schär (2017); [6] Polansek et al. (2018); [7] Masante et al. (2018); [8] Sly (2017); [9] Whittington et al. (2014); [10] Coffel et al. (2019); [11] Aziz et al. (2019); [12] Basheer et al. (2020); [13] Allam and Allam (2007); [14] European Political Strategy Centre (2019); [15] Meredith et al. (2019); [16] Hill et al. (2015); [17] Meier et al. (2014); [18] Challinor et al. (2018); [19] Russo et al. (2014); [20] Houze et al. (2011); [21]Mann et al. (2017)

we present a provisional operationalisation below via a set of six contrasting examples (Table 1). All elements of the framework are described for each case: categories of impact, recipients, triggers, impact transmission scales and dynamics, and response targets and dynamics. The variety of examples in the table shows that the framework can be operationalised in quite different contexts to describe and compare impacts between neighbouring regions in both developed and developing countries (e.g., Scandinavian and East African hydropower infrastructure), throughout complex international systems (e.g., manufacturing supply chains and agricultural commodity markets) and in regional hotspots (e.g., the Arctic).

As a means of demonstrating the framework in more detail, we have attempted to map some of the transmission dynamics involved in two of the cases shown in Table 1 (see Figs. 4 and 5). For each case, elements of the typology (shown in Fig. 3) have been combined to map the cascade of impacts (red arrows) between system components (blue boxes) and to highlight the potential targets of responses (green arrows).

4.1. Observed cross-border impacts of the 2011 Thailand floods

Fig. 4 expands on the example of the 2011 Thai flooding introduced in Section 1. Its cause was a compound event (Leonard et al., 2014; Zscheischler et al., 2020) – an unprecedented amount of rain falling on already saturated land – a phenomenon thought to be exacerbated by greenhouse gas induced climate forcing (Promchote et al., 2016). The underlying reasons for the severity of the impacts included failure by overseas investors to anticipate the high likelihood of flooding when locating facilities in the region, poor flood defences exacerbated by local land subsidence that magnified the hazard and a low effectiveness at accessing alternative supply networks and procurement sources to help mitigate the impacts (Haraguchi and Lall, 2015).

With respect to manufacturing supply chains, the initial impact was the inundation of seven major industrial estates located in the Bangkok hinterland. This led to the temporary closure of factories supplying key components to the car and electronics industries (choke points), with Japanese companies especially severely affected and severe delays

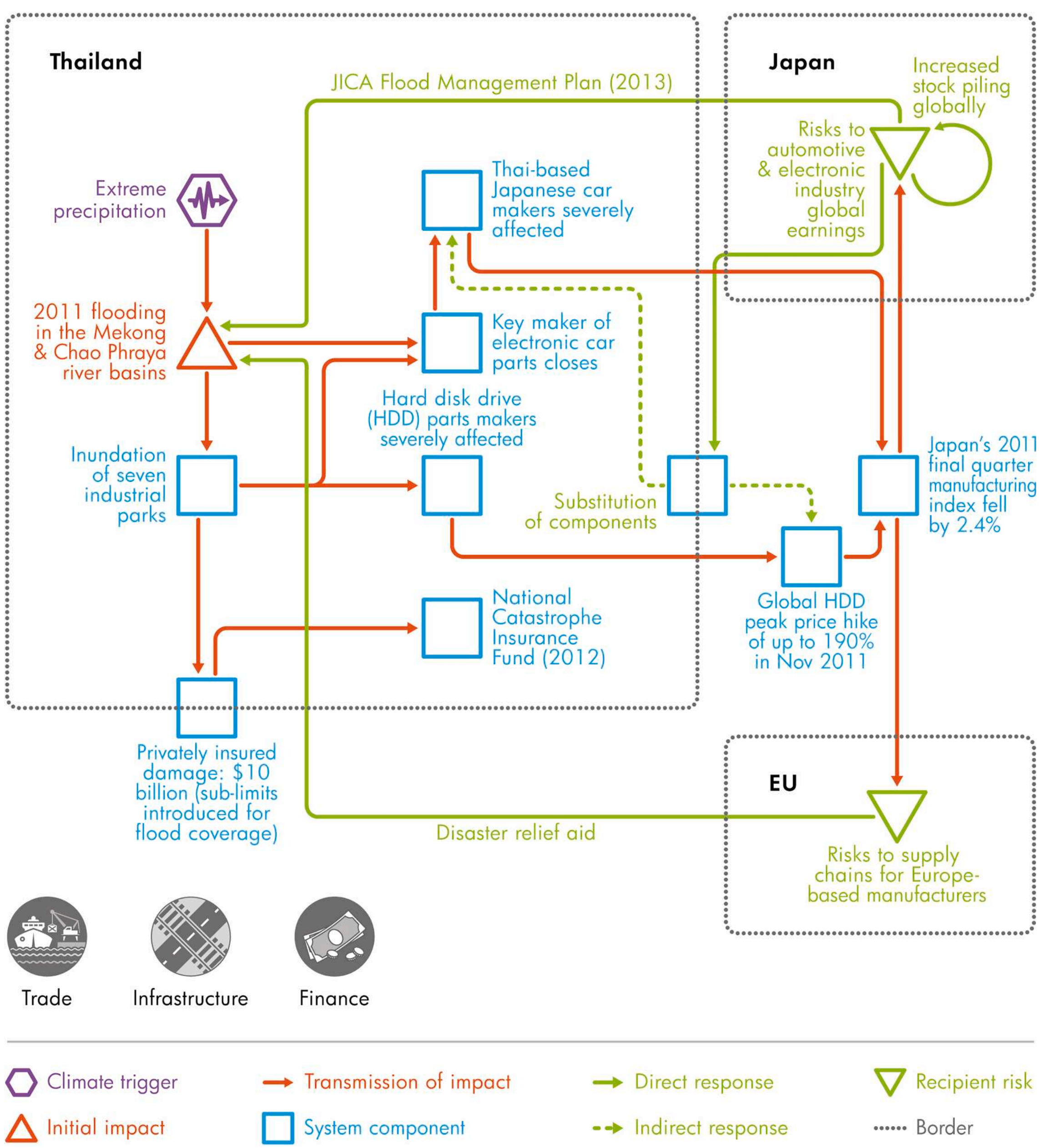

Fig. 4. Observed cross-border impacts of, and responses to, the Thailand floods of 2011 (for further explanation, see text).

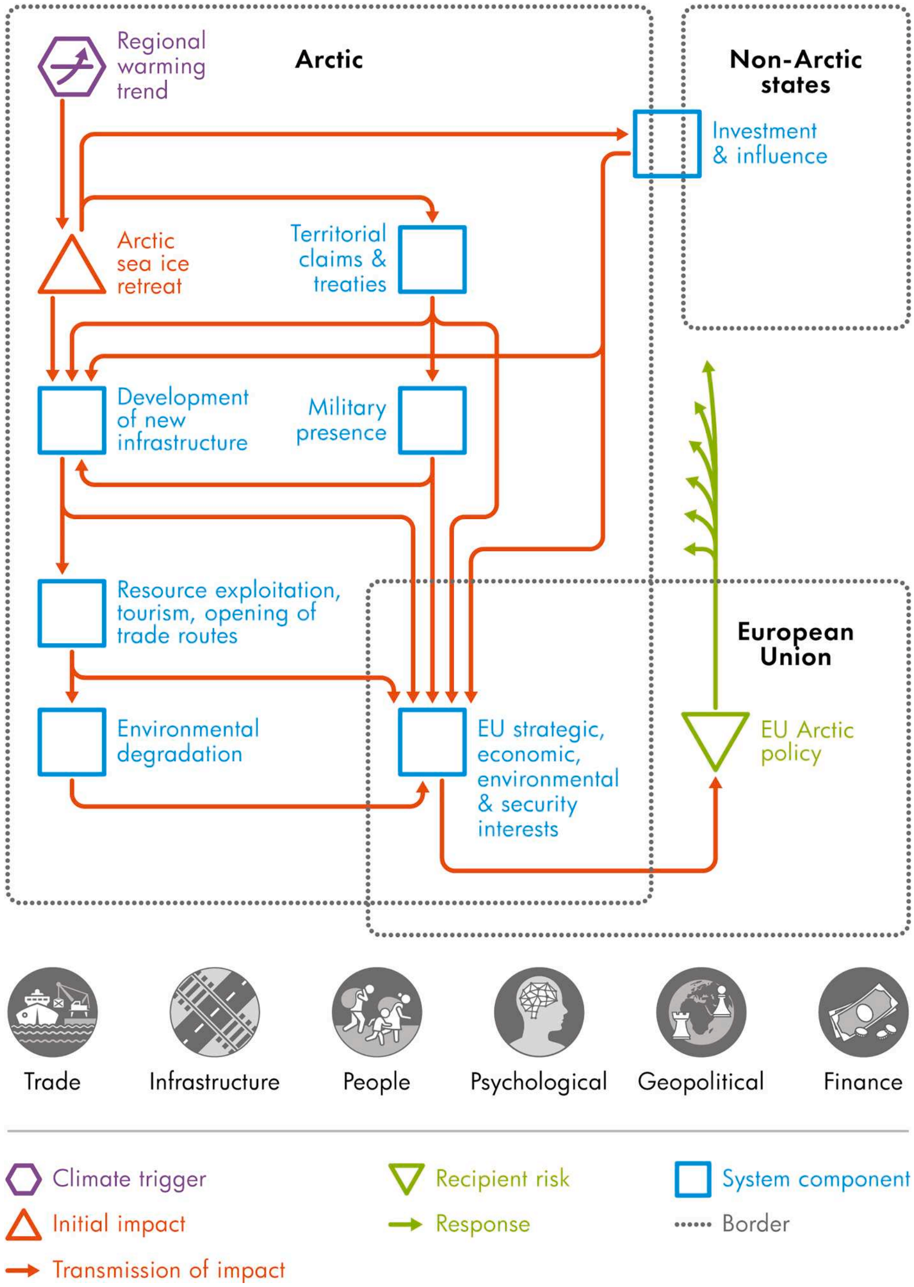

Fig. 5. Ongoing and potential cross-border impacts of Arctic sea ice decline (for further explanation, see text).

experienced in procuring substitute components from other sources unaffected by the flooding. Reduced production was felt globally and accompanied by a rise in prices. Some lessons were drawn in the finance sector, as insurers took a large hit (especially in Japan) and responded by introducing sub-limits for flooding. This induced the Thai government to introduce a National Catastrophe Insurance Fund to reassure international investors in regions likely to be susceptible to future flooding. Infrastructure damage was repaired with some assistance from disaster funds established abroad (including in the European Union). Japanese companies were the most exposed to the flood hazards, and responded by seeking to diversify component procurement sources, stock-piling components at a higher level than earlier whilst successfully lobbying for the Japan International Cooperation Agency (JICA) to invest in a Flood Management Plan for the Chao Phraya River. For more details, see Haraguchi and Lall (2015).

4.2. *Ongoing and potential cross-border impacts of Arctic sea ice decline*

Fig. 5 demonstrates how slow onset regional climate change can open up opportunities and risks for exploitation of the Arctic, with potential implications for EU policy in the region. Anthropogenic climate change is manifested as strong temperature increases in the Arctic region, a slow onset event whose initial impact is the retreat of Arctic sea ice. A decrease in summer sea ice area of more than 13% per decade has already been observed, half of which can be attributed to increased concentrations of atmospheric greenhouse gases (Meredith et al., 2019). The opening up of Arctic coastal regions and of natural resources previously inaccessible beneath the ice presents a theoretical opportunity for exploitation, driven by a wide range of economic and socio-political motives and processes unrelated to climate change. One of the first effects is the transboundary psychological impact of wide recognition of the change. This may lead to concrete actions by national, transnational and corporate actors propagating through an impact transmission system. Arctic states, including some EU member states, and private companies are already manoeuvring to stake their claims to territory and resources in the region, some backing this with military presence (Hill et al., 2015). Non-Arctic states are also competing to exploit new possibilities to invest in Arctic infrastructure to facilitate resource extraction, the opening of trading routes and tourism (Meier et al., 2014). These economic activities would also introduce acute hazards to the fragile Arctic environment. All these shifts impact the EU's interests and motivates its interest to seek influence in the region. Here, policies to protect EU interests in the Arctic, the recipient risk, may include diplomatic efforts to forward EU interests, investments in some of the economic opportunities, as well as policies to protect the Arctic environment (European Political Strategy Centre, 2019). Hence, although climate change is the underlying driver of change, any adaptation actions to address its consequences must necessarily account for the full gamut of non-climate drivers to ensure that such measures (e.g., the development of safety infrastructure to cope with increased marine traffic) and their related investments are both effective and coherent.

4.3. Challenges of operationalisation

Various challenges need to be overcome when operationalising the conceptual framework. These include the lack of specific scientific studies that describe in detail the links between different system components. It is therefore necessary, in many cases, to interpret patchy, often anecdotal evidence in order to connect changes, for example to attribute the role of an initial impact in driving a cascade of subsequent impacts. The difficulty of separating a climate cause from many other potential triggers of impacts and their transmission (e.g., economic, political, environmental or health-related triggers) is another formidable challenge. This is discussed further in section 5.5, below, in the context of wider systemic risks and their potential management.

Defining system boundaries for each case can also present challenges. By opening up the complexity of impact transmission systems, it is necessary to delineate the limits of those systems in order to concentrate on the system components – and the transmission of impacts – that are most relevant in driving the risk to a specified recipient. For instance, in the case of the 2011 Thailand floods it is necessary to decide which system components are vital to include for the purpose of mapping the risk to Japanese manufacturers from the initial flood event in Thailand. In this case, the available evidence (i.e., Haraguchi and Lall, 2015) indicated that the Japanese and global hard disk drive and car manufacturing supply chains were the most relevant system components to include, along with the finance sector for infrastructural reconstruction and climate-proofing. But this decision is to some extent arbitrary and could be made differently in a situation where there is either alternative or more robust evidence available, or if the recipient itself (or other recipients) are understood as being subject to or perceiving different types of risk (e.g., risks to food security in low income countries brought on in the same flooding by damage to 1.2 million hectares of Thai rice cultivation area and its effects on the world market price – Son et al., 2013). Thus the operationalisation of the conceptual framework is dependent on the type of evidence available, the choice of recipient region, decisions and assumptions about the risks of interest to recipients and the extent of system boundaries applied to each case.

5. Discussion

This section discusses the reasons why a conceptual framework describing cascading, cross-border climate change impacts is considered necessary and useful and how the framework introduced above contributes to this objective. At the outset, and in addition to national studies indicating their significance (see Introduction), a focus on the risks resulting specifically from climate change triggers can readily be justified from growing evidence in the literature. The IPCC Fifth Assessment Report concluded that "climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems…", some of which "…will have cascading effects" (IPCC, 2014, p. 14). In line with such trends, it is quite possible that cross-border climate change impacts will become more important in the future.

Then there are alternative possible framings of cross-border impacts. For example, some of these focus on other triggers of cross-border impact (e.g., non-climatic natural disasters, political or economic crises or shocks), or on categories of risk (e.g., food security risks or military and security risks). Framings may also adopt a user-oriented or "risk owner" perspective (Young et al., 2017) in contrast to a risk origin perspective (e.g., operational supply chain risk framing – Ghadge et al., 2020).

Relevant comparable frameworks exist in "non-climate" fields. For example, Keow Cheng and Hon Kam's (2008) framework for analysing risk in supply networks describes the role of different network structures (similar to our system components and typology in Fig. 3) as influencing the nature and pattern of risk transmission, mostly in industrial supply chains. In evaluating the risks themselves, there are parallels to be drawn with the "material criticality" approach used to assess risks to vital raw materials of importance in Europe. This evaluates supply chain risks as the product of a commodity's economic value and the likelihood of its disruption, related to its substitutability (Blengini et al., 2017). Examples also exist in the sustainable development literature, for example the tele-coupling framework introduced by Liu et al. (2013), which describes causes and effects with distinct "sending" and "spill-over" systems (similar to our impact transmission system) and "receiving" systems (similar to our recipient). Both of these non-climate focused frameworks aim to describe the flow of potential impacts between geographically separate systems.

The advantages of a detailed and comprehensive framework are fourfold: (i) it provides a common language with which to identify and assess cross-border impacts, (ii) it contributes to enhancing our understanding of those impacts by providing structure and clarity, (iii) it facilitates comparisons between studies on diverse aspects of cross-border impacts and (iv) it informs policy to reduce the risks such impacts pose to society. The remainder of this section looks into each of these points in more detail.

5.1. Providing a nomenclature

As noted, the first wave of studies that have emerged in recent years to identify and assess cross-border climate change impacts have used different terms and conceptualisations of the mechanisms via which climate change impacts in one place result in risks somewhere else. A nomenclature therefore needs to be provided and established to enable a more consistent and enriching dialogue between the various stakeholders implicated in the process of adapting toameliorate these risks, including those from various disciplines and fields of research and strategic planners from public, private and international sectors. The conceptual framework is an attempt to provide this nomenclature for each of the elements and mechanisms involved.

5.2. Enhancing understanding

The conceptual framework presented here can be used to identify and connect different bodies of existing knowledge about climate change from a range of disciplines. The field of climate change impacts, adaptation and vulnerability research is already a diverse and in some cases fragmented one, with significant challenges pertaining to the integration of knowledge across disciplines, sectors and – especially now given the emergence of cross-border impacts as an important theme – geographical scales (e.g., see Harrison et al., 2015). The conceptual framework presented here provides a mechanism for the transparent and systematic integration of evidence drawn from a diversity of scales and disciplines to enhance understanding of climate risk propagation.

The conceptual framework provides an architecture that can also be applied and evolved to improve the relevance of knowledge that is used to support the design of adaptation responses in an interconnected world. By combining a typology of impact transmission dynamics and typologies of response targets and response dynamics, the framework integrates the two separate but interrelated processes of impact and risk identification with response planning. This is especially important given the complex international context in which cross-border climate change impacts – and responses to these impacts – will occur. A framework such as this one, which makes explicit the interaction between impacts and responses, is particularly valuable for enhancing our understanding of the political and policy opportunities (and challenges) for global cooperation on adaptation. It also helps to widen recognition of global cross-border impacts, regardless of their causal origin, and the importance of systemic resilience.

5.3. Facilitating comparison

Given the broad scope of knowledge on and for adaptation (diverse disciplines, scales and geographies) it is both valuable and necessary to increase the comparability between adaptation case studies (Biesbroek et al., 2018). In addressing cross-border climate change impacts, adaptation planners will potentially need to consider a very diverse range of risks (i.e., across the categories depicted in Fig. 3b, such as trade, finance, biophysical and geopolitical impacts) and therefore be required to synthesise knowledge spanning multiple disciplines and compare between results with diverging levels of specificity and uncertainty. In this context, a conceptual framework such as the one presented above is potentially very useful. In Section 4 we illustrated how the framework enables comparison between illustrative cases. Fuller applications of the framework, via in depth case studies, would reveal in more detail how it can enable comparison between impacts, recipient risks and responses. This would both enhance adaptation knowledge but could also support more integrated adaptation planning.

5.4. Informing policy

The conceptual framework helps to inform policy in two principal ways. First, it supports adaptation planners from a single organisation in improving the relevance of their climate risk assessments. It does this by providing a structure that accommodates climate triggers and a range of possible impact transmission processes, many unrelated to climate, from beyond the jurisdictional border of the decision maker. This enables the identification and subsequent assessment of systemic risks and associated uncertainties, which can inform the design of responses to ameliorate these risks, hence accounting for climate within the wider context of enhancing resilience. Second, it helps to identify where cooperation between actors will be necessary or beneficial for implementing adaptation. It does this by helping to reveal where an actor within the response transmission system is somehow interdependent with system components that are under the control or influence of another actor or actors. This is particularly important as impacts and responses can be affected by the actions of a range of actors with differing motivations and representing interests of both the public and private sectors. For example, with reference to Fig. 4, applying the conceptual framework reveals to the coordinator of national adaptation planning in a country like Japan that employment and social stability there will be affected by impacts to international supply chains triggered by flooding events and the disruption caused to the manufacture of key components in countries like Thailand. This raises various options for adaptation, including awareness raising in the private sector on the need for diversification of component supply (see Kahiluoto et al., 2020), or increased cooperation between Japan and Thailand to explore measures and potentially even burden sharing, to increase the resilience of the links between Japan and Thailand in the face of increasing future climate threats (e.g., the JICA Flood Management Plan). The framework could also be applied to inform policy that seeks to reduce climate risks across entire systems, for example across international agricultural commodity markets, such as the soy case featured in Table 1.

The global nature of the adaptation challenge has been recognised relatively late in the international political process orchestrated by the UNFCCC. The establishment of the global goal on adaptation in Article 7.2 of the Paris Agreement (United Nations, 2015) may signify a new era in global cooperation on adaptation, but progress with implementation – and understanding of the role of cross-border climate change impacts as a driver for international cooperation – is slow and insufficient. Global governance of adaptation remains a contested topic, due in part to the poor definition or articulation of adaptation as a global problem (Persson, 2019). The conceptual framework helps to explain why and how adaptation is a global challenge with international dimensions.

5.5. Limitations of the conceptual framework

The framework presented above is research-oriented more than it is user-oriented. Its focus on climate change triggers means that it emphasises the origins of cross-border impacts at the expense of other categories of risk or risk ownership. As such, it may be more effective in its current form for organising research and structuring and comparing knowledge about society's exposure to climate risk, than as the basis for a practical tool to support decision making. A climate focus also has the danger of downplaying other risks (e.g., triggered by political, economic, geophysical or health circumstances) whose solutions may share many features of those advocated to address climate risks. For example, the COVID-19 crisis has drawn attention to the risks of geographical concentration and lack of resiliency in supply chains for semiconductor companies (McKinsey & Company, 2020; Deloitte, 2020) as well as via interconnected global networks more generally (van den Hurk et al., 2020). This points to the need for careful contextualisation of studies of cross-border impacts and their responses, so that insights can be used to support the building of resilience across a range of systemic risks.

The framework is also likely to be incomplete in its coverage of specific mechanisms and typologies of impact and response dynamics, as well as of scales and response targets. Further testing, in a diverse range of sectoral, geographic and data-rich contexts, will be needed to improve its coverage and fill gaps in the current typologies.

The framework also focuses in its current form more on impact transmission than response transmission. Its primary objective is to provide a nomenclature and structure to raise awareness about and enhance understanding of cross-border impacts. However, the complexity, scale, drivers, effects, feedbacks and interaction between responses are likely to be more far reaching than is suggested in this current version. Further theoretical and empirical analysis of the governance of cross-border climate change impacts is needed to inform the development of a more sophisticated response-focused framework.

5.6. Future research

A number of opportunities exist to use and improve the framework. Ex-ante applications of the conceptual framework in novel research projects will help to test and hopefully refine the elements and overall composition of the framework. Detailed empirical case studies that operationalise the elements of the framework are therefore encouraged.

The conceptual elements identified could be built on to develop a modelling framework or modelling protocols to support improved quantitative assessment of cross-border climate change impacts. Arguably, the potential of existing quantitative assessment methods of different types has not yet been realised in the context of assessing cross-sector impacts (Challinor et al., 2018), though examples are available of computable general equilibrium models being applied to assess the cross-border dynamics of climate impacts at the global scale (e.g., see Schenker, 2013; Schenker and Stephan, 2014). Some elements described in the framework (i.e., triggers, impact and response transmission dynamics and their feedbacks) are typically addressed using different types of computational models, in many cases applied to different sectors. Though challenging in its complexity, non-linearities and uncertainties, there may be potential, nonetheless, to use the conceptual framework to inform the integration of modelling components in new ways. Moreover, even without full model integration the framework can be used to support the interpretation of different model results, hence enhancing our understanding of cross-border climate change impact transmission and the potential mediating effect of policy responses in complex cross-border systems.

Another device for exploring and describing case examples that have been operationalised using the framework could be through analysis of climate event storylines (e.g., Shepherd et al., 2018; Shepherd, 2019). This involves mapping complex cross-border impacts that have been observed in order to improve the understanding of the processes, interactions and dynamics of the sort illustrated in Fig. 3. It also makes use of counterfactuals to explore hypothetical worst case scenarios or to test the effectiveness of policy responses (see Section 2).

Furthermore, while the scope of the paper focuses on climate-related risks, we believe the conceptual framework we propose could be utilised fruitfully to explore other dimensions of cross-border risks not driven by climate. For instance, it could be merged with the more practical analysis being developed on cross-border financial contagion risks (Bricco and Xu, 2019) to understand more clearly their drivers, transmission channels and impacts.

Finally, the evolution and application of this research-targeted framework into a more user-oriented format would help to realise its potential contribution for improving adaptation decision making and outcomes. This could be by way of providing groundwork for preparing guidance or even developing a decision support tool for national adaptation planners.

6. Conclusions

Cross-border climate change impacts have received limited attention to date. The cases we have reviewed demonstrate their potential disruptive force. Global interconnections create complex dynamics that are challenging to trace and understand. This also complicates the design and implementation of adaptation responses. A conceptualisation of cross-border impacts is a first step towards understanding them. The conceptual framework presented here provides a simple, but flexible, structure to describe and analyse cross-border climate impacts and their consequences. It offers a foundation for consistent comparisons of different patterns of cross-border impacts in different sectors and geographies. It can also be used to inform adaptation planning. The framework can help in the identification of subtle dynamics that may guide new empirical research and data collection as well as model development. In particular, with systematic application of the framework it is possible to highlight gaps in our existing understanding of system dynamics, or gain new insights into particular leverage points within the system. These can be targeted in order to find ways of building resilience to climate change in the region of origin, along the impact transmission system and in the recipient region exposed to the propagated risk.

CRediT authorship contribution statement

Timothy R. Carter: Conceptualisation, Investigation, Writing - original draft, Writing - review & editing, Visualisation, Project administration. **Magnus Benzie:** Conceptualisation, Investigation, Writing - original draft, Writing - review & editing, Visualisation. **Emanuele Campiglio:** Investigation, Writing - review & editing, Visualisation. **Henrik Carlsen:** Conceptualisation, Investigation, Writing - review & editing, Visualisation. **Stefan Fronzek:** Conceptualisation, Investigation, Writing - review & editing, Visualisation, Project administration. **Mikael Hildén:** Conceptualisation, Investigation, Writing - review & editing. **Christopher P.O. Reyer:** Conceptualisation, Investigation, Writing - review & editing, Visualisation, Project administration, Funding acquisition. **Chris West:** Conceptualisation, Investigation, Writing - review & editing, Visualisation.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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