Visualizing the Interconnections Among Climate Risks

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Key Points:
- The paper developed a methodology for visualizing how climate change can generate various risks and how they can be interconnected
- We identified 91 climate risks and 253 causal relationships among them based on a literature survey and graphically presented the interconnected risks
- We found that changes in the climate system impact natural and socioeconomic systems, ultimately influencing human security, health, and well-being

Supporting Information:
- Supporting Information S1
- Figure S1
- Table S1
- Table S2

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Visualizing the Interconnections Among Climate Risks

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Abstract It is now widely recognized that climate change affects multiple sectors in virtually every part of the world. Impacts on one sector may influence other sectors, including seemingly remote ones, which we call "interconnections of climate risks." While a substantial number of climate risks are identified in the Intergovernmental Panel on Climate Change Fifth Assessment Report, there have been few attempts to explore the interconnections between them in a comprehensive way. To fill this gap, we developed a methodology for visualizing climate risks and their interconnections based on a literature survey. Our visualizations highlight the need to address climate risk interconnections in impact and vulnerability studies. Our risk maps and flowcharts show how changes in climate impact natural and socioeconomic systems, ultimately affecting human security, health, and well-being. We tested our visualization approach with potential users and identified likely benefits and issues. Our methodology can be used as a communication tool to inform decision makers, stakeholders, and the general public of the cascading risks that can be triggered by climate change.

Plain Language Summary The paper demonstrates in a most holistic manner how climate change can generate various risks and how they are actually interconnected. Based on a literature survey using the Intergovernmental Panel on Climate Change Fifth Assessment Report, we identified 91 climate risks and 253 causal relationships among them and graphically drew such interconnected risks. We found that changes in the climate system impact the natural and socioeconomic system, influencing ultimately human security, health, and well-being. This indicates that climate change can trigger a cascade of impacts across sectors. Our findings point to the need to address the climate risk interconnections in impact and vulnerability studies. We tested our visualization approach with potential users and identified likely benefits and issues. The implications of our study go beyond science. Our study is useful to inform stakeholders of a broad yet fresh perspective of climate risks that have not been presented before.

1. Introduction

Socio-economic activities in the present world are increasing their interdependencies because of rapid technological progress, urbanization, and the globalization among others (World Economic Forum, 2018).

Awareness has been raised that the natural world—for example, ecosystems susceptible to climate change—is a system comprising interwoven processes affecting one another (Scheffer et al., 2001). The Earth system as a whole, a dense network of interrelated processes, may exhibit strongly nonlinear responses and unexpected behaviors (Lenton et al., 2008; Steffen et al., 2018). There is a dire need to understand the resilience of such complex systems.

Climate risks may ripple through sectors in the present interdependent world, posing a challenge ahead of us to maintain the resilience of the system (Helbing, 2013). Being consistent with the way in which International Risk Governance Council (2005) defines risks, we use this term to refer to both positive and negative potential impacts of climate change on various ecosystems and human society. The risks of climate change can be transmitted and amplified through multiple direct and indirect pathways (Liu et al., 2015; Pidgen et al., 2003). A combination of interacting processes across a wide range of spatial and temporal scales can result in extreme impacts (Leonard et al., 2014). The magnitudes of risks may be significantly underestimated if we fail to consider their interconnections (Challinor et al., 2017). Several efforts in this regard have been made, but these have been mostly at the country or regional level. For example, the Third National Climate Assessment conducted in the United States analyzed the domestic impacts of climate change on cross-sectoral systems and the cascading effects across sectors (Jacobs et al., 2016). The UK's Second Climate Change Risk Assessment (UKCCRA2) systematically assessed the risks to the UK posed by climate change (Challinor et al., 2016). The UKCCRA2 reports are not intended to provide comprehensive visualizations nor assessments of interactions; rather, they serve to identify particular areas where government policies need to be coordinated and aligned (Street et al., 2016). The fourth report for the assessment of climate change impacts and vulnerability in Europe (Lung et al., 2017) reviewed the ways in which the impact of climate change in one sector affects other sectors across the continent. In another Europe-focused study, Harrison et al. (2016) showed that single-sector studies tend to misrepresent the magnitude of climate-sensitive impacts because they omit the complex interdependencies within human and environmental systems. Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) identified a number of global climate risks (Birkmann et al., 2014; Hewitson et al., 2014; Oppenheimer et al., 2014). The IPCC AR5, however, classified the global and regional risks according to regions and sectors, and the causal chain of climate risks has not been examined systematically nor visualized effectively.

A user-friendly visualization of interconnected climate risks can serve as a powerful way to deliver climate risk information to the general public (Herring et al., 2016). Visualization has long been known to have a variety of cognitive benefits when compared to written information (Sheppard, 2005). Visualizing the chains of risk transmission in a clear and compelling way is likely to help the layman better understand the broad scope of climate risks. Whereas network visualizations have been used in fields such as economics, linguistics, computer science, and biology (Lima, 2011), few attempts have been made in the context of climate change.

In this paper, we present a first step toward the goal of effectively visualizing climate risks and their cause–effect relationships based on a survey of literature. In doing so, we generated a database of climate risks and their interconnections on a global scale. Working with a visualization expert, we developed a practical methodology for visualizing chains of climate risks. The visualized network is intended as a communication tool to educate stakeholders and to help raise awareness of the complex and interconnected nature of climate impacts.

The remainder of the paper is organized as follows: section 2 describes the methods of our literature survey and visualization of climate risk interconnections. Section 3 presents the visualized networks of risk interconnections. Section 4 discusses the implications of our visualization approach and reports the outcome of the test use of our visualized products. The paper is concluded in section 5.

2. Materials and Methods

2.1. Literature Survey of Climate Risk Interconnections

The literature survey was performed as a part of the Integrated Climate Assessment–Risk, Uncertainty, and Society (ICA-RUS) project (Emori & Takahashi, 2018; Emori et al., 2018; ICA-RUS 2012). Several project members were assigned to each of the seven sectors prone to climate risks (1: water, 2: food, 3: energy, 4: industry and infrastructure, 5: disaster and security, 6: health, 7: ecosystems), which are consistent with the chapters in IPCC WG2 AR5 (hereafter WG2 AR5; details in the supporting information). Each group conducted a literature search to identify climate risk items within the assigned sector, as well as the associated cause–effect relationships. We considered papers cited in WG2 AR5 but also looked to additional sources when appropriate or necessary. The selection of risk items and causal relationship was determined by the expertise of the project members—in other words, each researcher reports what he/she thinks are relevant climate risks and their possible impacts. We did not employ text mining techniques. Table S1 shows the areas of expertise of project members in charge of the literature review. In order to minimize any bias, a minimum of two researchers conducted the literature survey for each sector. Our literature-based approach differs from the approach taken by the World Economic Forum (2018), which conducted a global risk assessment and generated a risk interconnection map, based solely on expert opinions elicited via questionnaires collected from meeting delegates.

It should be noted that "ecosystems" refers to a functional unit consisting of living organisms and nonliving environments, following the definition in IPCC WG2 (Agard et al., 2014). Nonliving components related to the climate drivers (i.e., physical changes in atmosphere, land, and ocean) are not included in the "ecosystems." In addition, ecosystems in our study consists of risk items related to natural ecosystem. Risk terms related to ecosystem services (MA 2005; Häyhä & Franzese, 2014) are included in sectors such as food (e.g., crop, fishery), water (e.g., river, lake), industry (e.g., timber), and energy (e.g., hydropower), as well as ecosystems.

Although the term "sector" (i.e., a branch of the economy or society) is not strictly applicable to ecosystems, we treat ecosystems as one of the sectors in the present paper. Ecosystems (or biomes) are sometimes treated as one of the sectors by the community of climate impact modelers (e.g., Inter-Sectoral Impact Model Intercomparison Project; https://www.isimip.org/about/#sectors-and-contacts).

We accounted for a variety of impacts, including those which could be considered beneficial in order to address potential impacts as widely as possible. Our choice of risk factors is not restricted to particular places and levels of impact. We considered impacts only by climate change and did not take into account the effects of mitigation or adaptation. The time scale of our analysis is about 100 years. Impacts on longer time scales (e.g., a subset of tipping elements such as the collapse of thermohaline circulation; Lenton et al., 2008) are beyond the scope of the present paper. (In fact, the risks associated with tipping elements are investigated by another team in the ICA-RUS project; Iseri et al., 2018.) The level of detail in impact representation was kept consistent across sectors through discussion among project members. For instance, impacts on the production of wheat, soybean, maize, and rice are lumped together as impacts on crop production. Likewise, damages to various types of infrastructure (roads, bridges, port facilities, dams, power plants, etc.) are summarized as infrastructure damage.

Furthermore, we also considered climatic drivers, which we defined as physical changes in the global climate system caused by the emissions of climate forcers, such as an increase in air temperature or a decrease in precipitation. Additionally, we considered an increase in GHG concentrations as a climate driver, the direct consequences of which are, for example, an increase in ecosystem production (i.e., CO_2 fertilization effects) or ocean acidification (Table 1). However, we did not account for the impacts from air pollution, including those indirectly caused by climate change (e.g., impacts on health from an ozone increase due to temperature changes; Shen et al., 2016).

We identified a total of 87 risk factors that can be associated with the seven sectors and 17 climatic drivers (Table 1). In all, 253 causal relationships were identified (Table S2). For references regarding the risk factors and climate drivers and their causal links, we cited IPCC AR5 chapters wherever possible.

2.2. Definition of Natural, Socioeconomic, and Human Systems

We also categorized climate risks into natural, socioeconomic, and human systems in order to portray the overall structure of climate risk interconnections to be discussed in section 3.2. In this classification, we defined the "human system" risks as risks in sectors closely related to human life, which corresponds to the health, disaster, and security sectors. The risks in these sectors are summarized in the final part of Part A in IPCC WG2 AR5 titled "Human health, well-being, and security" (sections 11–13; details in the supporting information).

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Table 1
List of Climate Risks and Climate Drivers Created Based on Our Literature Survey

Sector/Driver	No	Risk Item	References
Water	1	Decrease in river discharge	a, b, c, d, e
	2	Increase in river discharge	a, f
	3	Decrease in soil moisture	a, f
	4	Increase in soil moisture	a, g
	5	Rise in river water temperature	a, b
	6	Worsening of river water quality	a, h
	7	Salinization of coastal waters	a
	8	Rise in lake water temperature	a
	9	Worsening of lake water quality	a
	10	Worsening of groundwater quality	a
	11	Decrease in groundwater table	a
	12	Decrease in water resources	a
	13	Increase in water resources	a
	14	Increase in water demand	a
	15	Increase in water treatment costs	a
	16	Rise in water prices	a
Food	17	Decline in crop production	c, d, i, j, k, l, m
	18	Increase in crop production	c, d, i, j, k, l
	19	Decrease in pasture production	c, i, l
	20	Increase in pasture production	c, i, l
	21	Decrease in livestock production	d, i, j, l
	22	Increase in livestock production	c, d, j
	23	Increase in plant disease	f
	24	Increase in damage to agricultural land	n, k
	25	Decrease in fisheries catch	o
	26	Increase in fisheries catch	o
	27	Change in food distribution	j
	28	Change in food trade	l
	29	Rise in food prices	i
	30	Rise in livestock feed prices	i
	31	Destabilization of food supply	i, j, l
Energy	32	Decline in hydropower efficiency	c, d
	33	Increase in hydropower efficiency	a
	34	Decline in thermal power efficiency	a, b
	35	Decline in nuclear power efficiency	b
	36	Increase in air conditioning demands	b, p
	37	Decrease in heating demands	b, p
	38	Increase in energy demands	a, b, p
	39	Rise in energy prices	b, q
	40	Destabilization of energy supply	a, b, p
Industry and infrastructure	41	Increase in infrastructure damage	a, b, j, p, r
	42	Adverse impacts on tourism	b, o
	43	Decrease in lumber production	f, s
	44	Increase in lumber production	f
	45	Appearance of the Northern Sea Route	t
Ecosystems	46	Decrease in ecosystem production*	e, f, h
	47	Increase in ecosystem production*	f, h
	48	Increase in soil erosion*	f
	49	Decrease in soil organic matter*	f, h
	50	Excessive algal growth**	a, f
	51	Increase in wildfires*	b, f, h, s, u
	52	Increase in forest decline**	f
	53	Change in vegetation zone**	f, h
	54	Decrease in mangroves and marshlands**	r
	55	Increase in insect pests**	f, i
	56	Decrease in insect pests**	f, j
	57	Loss of biodiversity**	e, f, r
	58	Increase in biodiversity**	f
	59	Decrease in marine ecosystem production***	o
	60	Decrease in ocean nutrients***	h, o, v

Table 1 *(continued)*

Sector/Driver	No	Risk Item	References
	61	Increase in dissolution of calcium carbonate***	h, o, r
	62	Ocean oxygen depletion***	h, o, v
	63	Change in marine habitats***	o
	64	Loss of ocean biodiversity***	o
Disasters and security	65	Worsening of water security	a, u, w, x
	66	Worsening of food security	i, u, w, x
	67	Worsening of energy security	b, q, p, y
	68	Adverse impacts on island regions	b, o, z
	69	Damage to cultural heritages	k, n
	70	Change in human migration	u, w
	71	Intensification of conflicts	u, x, aa
	72	Increase in flooding	a, b, g, i, m, n, p, r, w, u
	73	Increase in sediment disasters	a, b
	74	Increase in housing damage	a, p, r, t, w
	75	Increase in maritime accidents	r
	76	Increase in drowning accidents	r
Health	77	Increase in mortality due to heatstroke	n, u, y
	78	Decrease in mortality due to cold	n
	79	Increase in diarrhea	u
	80	Increase in malnutrition	u, ab, ac
	81	Increase in water-borne infections	u, ab, ad
	82	Increase in food-borne diseases	u, ab, ae
	83	Increase in animal-borne infections	u, ac
	84	Decrease in animal-borne infections	u
	85	Increase in human-to-human infections	ac, ad, ae
	86	Exacerbation of PTSD and other mental disorders	u, af
	87	Increase in respiratory diseases	u
Climatic drivers	1	Increase in GHG concentrations	h
	2	Decrease in GHG concentrations	h
	3	Air temperature rise	g
	4	Increase in extreme heat	g
	5	Decrease in precipitation	g
	6	Increase in precipitation	g
	7	Sronger tropical cyclones	g
	8	Increase in heavy rainfalls	g
	9	Increase in storm severity	g
	10	Stronger high tides	r, ag, ah
	11	Increase in snow and ice melting	g
	12	Increase in frozen soil thawing	g
	13	Change in seasonal cycles	g
	14	Rise in ocean temperature	g
	15	Rise in sea level	a, g, ai
	16	Changes in ocean circulation	g, ai
	17	Ocean acidification	h, o, r

Note. The risks are grouped into seven sectors (1: food, 2: water, 3: energy, 4: industry and infrastructure, 5: disaster and security, 6: health, 7: ecosystems). We indicate the direction of change accompanied by climate change (increase and decrease) for each of the risk items. In "ecosystems," the risks marked with * are risks related to ecosystem production (Figure S7), ** indicates risks related to biodiversity (Figure S6), and *** indicates risks related to the ocean ecosystem (Figure S8). In the "reference" column, the letters (a–z and A–L) indicate citations in the footnote.
[a]Jiménez-Cisneros et al. (2014). [b]Arent et al. (2014). [c]Romero-Lankao et al. (2014). [d]Magrin et al. (2014). [e]Cramer et al. (2014). [f]Settele et al. (2014). [g]Collins et al. (2013). [h]Ciais et al. (2013). [i]Porter et al. (2014). [j]Niang et al. (2014). [k]Hijioka et al. (2014). [l]Reisinger et al. (2014). [m]Kovats et al. (2014). [n]Seneviratne et al. (2012). [o]Pörtner et al. (2014). [p]Revi et al. (2014). [q]Bruckner et al. (2014). [r]Wong et al. (2014). [s]Kirilenko and Pand-Sedjo (2007). [t]Larsen et al. (2014). [u]Smith et al. (2014). [v]Rhein et al. (2013). [w]Adger et al. (2014). [x]Hsiang et al. (2013). [y]Anderson and Belle (2012). [z]Nurse et al. (2014). [aa]Kelley et al. (2015). [ab]Pawari (1999). [ac]Dubos (1965). [ad]WHO (2016). [ae]Estrada-García and Mintz (1996). [af]Berry et al. (2010). [ag]Olsson et al. (2014). [ah]Masson-Delmotte et al. (2013). [ai]Church et al. (2013).

The risks of other sectors (water, food, energy, industry and infrastructure, ecosystems) are classified into the "natural system" or "socioeconomic system." Specifically, if a risk is only related to the natural environment, the risk is categorized as a "natural system" risk. On the other hand, if the risk concerns society or the economy, it is classified as a socioeconomic system risk. The corresponding relationship between the WG2 AR5 chapters and the natural, socioeconomic, and human systems is described in the supporting information.

2.3. Visualization of Climate Risk Interconnections

2.3.1. Network Map of Climate Risk Interconnections

We present a method for generating figures so that individual risk interconnections are visually traceable. Since the number of cause–effect relationships between climate risks in our database is quite large (Table S2), including all the causal connections in a single visualization would result in an overly complicated representation. Figure S1 shows an overall network map encompassing the full array of cause–effect climate risk relationships listed in Table S2, using simulations based on the force-directed graph drawing (FDGW) technique by Fruchterman & Reingold, 1991 (hereafter FR91). The FDGW technique is one of the methods available for visualizing complicated network data.

The FDGW algorithm of FR91 is capable of generating a network diagram under several fundamental objectives. These include (1) distributing the vertices evenly in the frame, (2) minimizing edge crossings, (3) making edge lengths uniform, (4) reflecting inherent symmetry, and (5) conforming to the frame. The primary advantage of the FR91 algorithm is its ability to produce graphs using a simple simulation. Figure S1 was drawn with the R package "igraph" (Csardi & Nepusz, 2006) which uses FR91. We also used igraph to generate the network diagram between sectors (Figure 1), but the positions of the nodes were rearranged manually.

As is apparent here, including all the causal connections in a single visualization produces a highly complicated representation. In fact, the resulting agglomeration of nodes and edges shown in Figure S1 is virtually incomprehensible in a single view. To deal with the complexity of the overall network map, we divide the causal connections of climate risk based on the seven sectors and present the network of risk interconnections in eight segments in order to examine the interconnections for each sector in more detail. We begin by selecting the risk items of each sector and their cause–effect relationships; a network diagram of these causal links is then generated. Since ecosystems as defined in section 2.1 includes a large number of causal relationships, it is divided into two—the ocean and land ecosystems. The land ecosystem is further broken down into factors related to biodiversity and ecosystem production. On the other hand, the energy, industry, and infrastructure sectors are aggregated into a single figure since the number of items is relatively small and the climate risks in these sectors are closely interconnected.

Given the selected cause–effect relationships, network diagrams are first generated using the FDGW technique. Figure S2 shows the preliminary network diagram for the food sector simulated by the FR91 algorithm. Since the number of nodes is substantially smaller than the number of nodes in the overall diagram (Figure S1), the text for each of the risk items can now be included. However, the causal links are still not easily traceable since nodes and arrows are overlapped in many cases. This is partly because the diagrams are two-dimensional projections of the original three-dimensional layout.

To address this issue, the initial FR91 network diagram is refined by our graphic designer so that the risk interconnections are more easily traceable. We call the refined visualization a "network map" (Figures 2 and S4a–S10a).

The refinement procedure begins with examining the network diagram simulated by the FR91 algorithm and determining the cluster or topology of the network. There are several common network topologies, including bus, star, and ring types (e.g., Groth & Skandier, 2005). The nodes (climate risk items) and edges (causal relationships) of the network are arranged by reference to these topologies.

The nodes and edges are further arranged based on a "grid layout" technique (e.g., Muller-Brockmann, 1996), which is widely used for web design and printed materials. We allocate the nodes at the grid points by assuming grid lines in the background. The edges are arranged to have symmetrical direction, equal length, and minimal crossing wherever possible. The size of each risk item is adjusted to reflect the number of interconnections leading to or arising from the particular item.

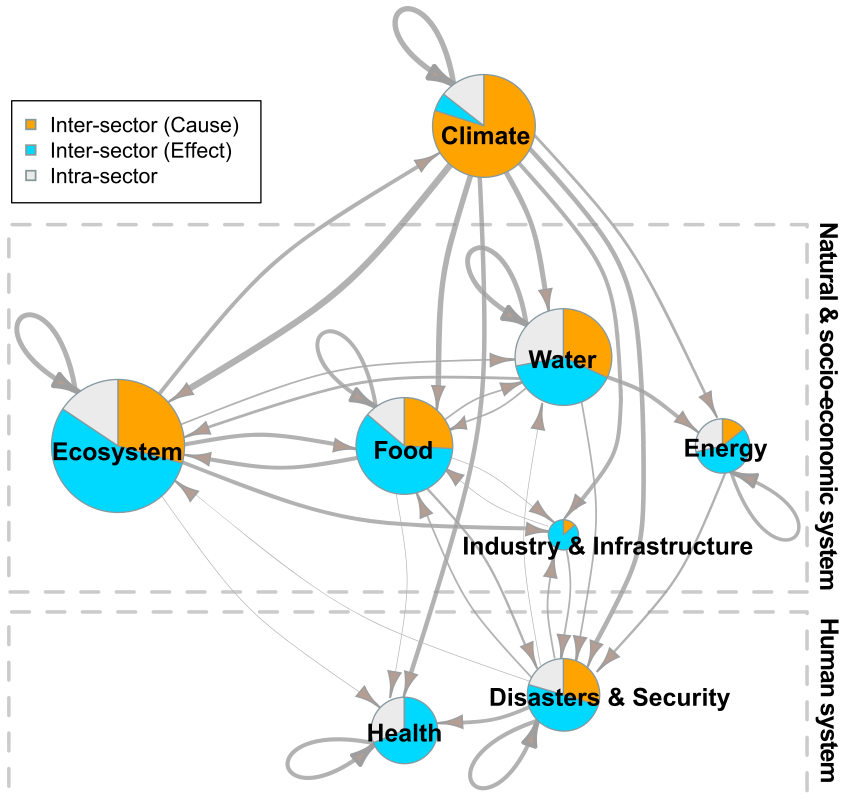

Figure 1. Climate risks and their cause–effect relationships shown at the sectoral level. The arrow thickness indicates the number of risk interconnections represented. Arrows connecting different sectors indicate intersectoral causal relationships, and those looping back to the same sector represent the causal links within the sector. The node size also reflects the number of risks identified within the sector. The colors of nodes indicate the portion of intersector cause (orange), effect (blue), and intrasector cause and effect (gray). For example, in a linkage between "increase in flooding" (water) causing "increase in damage to agricultural land" (food), as shown in Table S2, the former is an intersector cause, and the latter is an intersector effect. This linkage is represented by an arrow from the water to food sector. In a linkage such as "change in food distribution" (food) leading to "destabilization of food supply" (food), where both are an intrasector cause and effect. This linkage is represented by an arrow starting and looping back to the food sector. The upper and lower dashed gray rectangles encompass sectors related to the natural and socioeconomic systems and the human system, respectively.

For ease of understanding, the nodes (risk items) are shown as icons with text included. To produce a visualization that is universally accessible, we use color combinations that are color-blind friendly. Our visualizations feature sharp contrasts between the high brightness background colors and the thick black characters used in the text in order to maximize readability (Okabe & Ito, 2010). To differentiate climate risks for the various sectors, we use different shapes as well as different colors for the risk icons so as not to be completely dependent on color coding.

Furthermore, we show the cause–effect relationships related to the decline in crop production as an example (Figure 3). The risk interconnections are visualized depending on climate, natural, socioeconomic, and human systems (sections 2.2 and 3.2), and represented step by step in the form of PowerPoint animation format (supporting information). In the PowerPoint format, the causal relationships are shown by directional flows along the arrows, and nodes and arrows appear as figure develops, which would be helpful to understand the structure of climate risk interconnections.

2.3.2. Network Flowchart of Climate Risk Interconnections

We present a second form of visualization that we identify as a "network flowchart" (Figures 4 and S4b–S10b). In the network flowchart, we place items of change in the climate system in the upstream and those in the human system in the downstream, based on the understanding of overall structure for risk interconnections (sections 2.2 and 3.2).

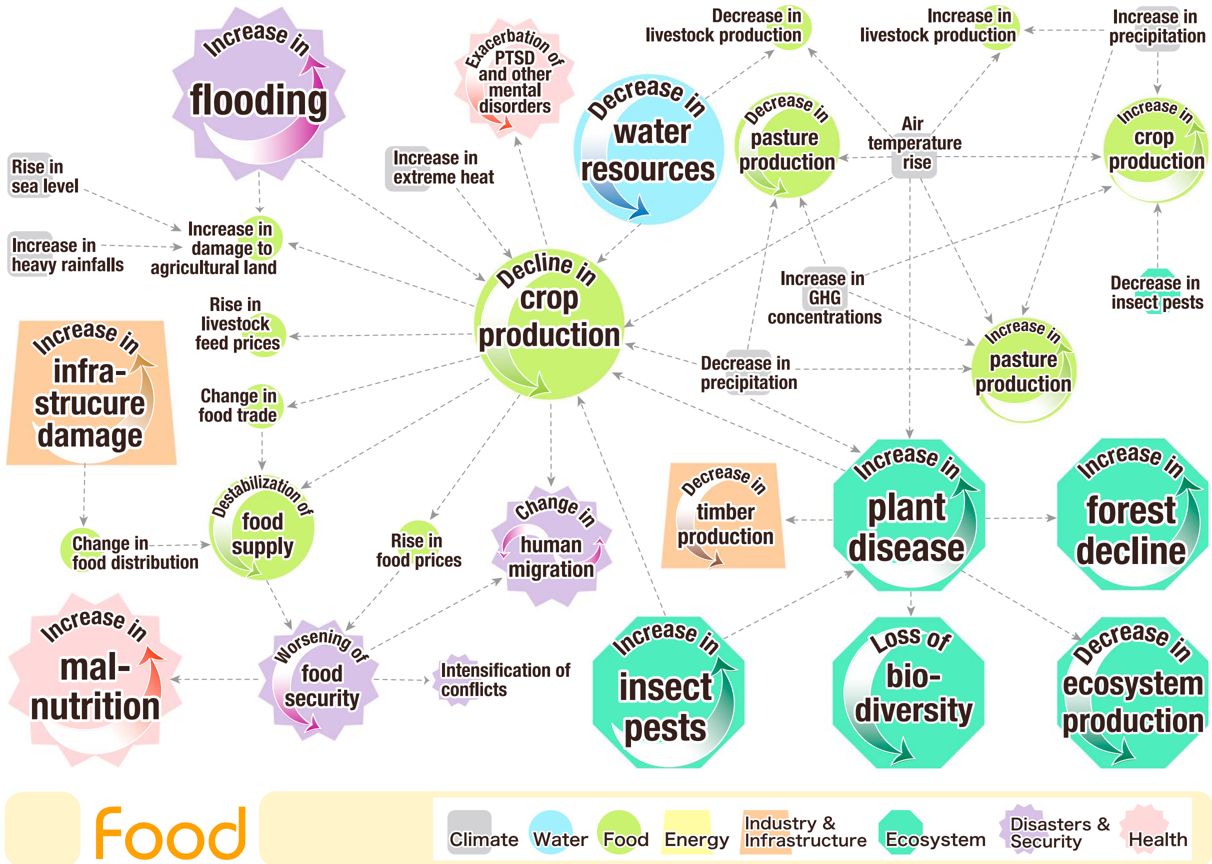

Figure 2. Map of climate risk interconnections related to the food sector. The size of each node reflects the number of causal relationships associated with the nodes. The color of nodes indicates a sector of the risk terms. Thick arrows within the icons indicate the directions of change (for example, "decline" is accompanied by a downward arrow). For the sake of discussion, we also include the risk interconnections related to the worsening of food security and increase in plant disease.

To produce the network flowchart, we first divide the entire network of risk interconnections into eight segments, as done for the network map. Next, a flowchart of the climate risk cascade is simulated by Microsoft Visio, which has the capability to flexibly simulate flow diagrams (Figure S3). Our designer then visually inspects the simulated flowchart and relocates the nodes, placing causes on the left side and results on the right. As in the case of the network map, the grid-layout technique is used to position the nodes in a way that minimizes edge crossings. The color and shape of the various nodes are the same as those used in the network map.

The underlying data are consistent for the network map (Figure 2) and flowchart (Figure 4) pairs; the difference in the two presentation forms is merely the layout (i.e., the position of the nodes and arrows). The network map and flowchart are designed for different purposes. While the network map is a more powerful tool for presenting individual cause–effect relationships, the network flowchart allows one to follow the cause–effect chains more easily from upstream to downstream.

2.3.3. Nodes and Arrows in the Network Map and Flowchart

In the sector-specific risk network maps and flowcharts, risk items having eight or more linkages (upper 13th percentile) are shown in large nodes. Those with four or more but fewer than eight linkages are shown in medium nodes (upper 43th percentile); the remaining risks are shown in small nodes. We should note that the diagrams show all the interconnections within a particular sector; this mean that some risk items may be shown in large icons despite the fact that only a small number of linkages actually appear in the figure. For example, "increase in infrastructure damage" (a risk term in the energy and infrastructure sector), which is shown with just one connection in the food sector, is represented by a large icon in the food sector figure because this risk term has more than eight interconnections with sectors other than the food sector. Based on the same principle, a causal link from "increase in flooding" to "exacerbation of PTSD and other

Figure 3. Network map of climate risk interconnection related to the term "decline in crop production." Cause–effect relationships concerning (a) climate diver, (b) climate driver and natural system, (c) climate driver and natural and socioeconomic systems, and (d) climate driver and natural, socioeconomic, and human system are illustrated.

mental disorders" (Norris et al., 2002) appears in Figure S9 (disaster and security sector) and Figure S10 (health sector) but not in the food sector (Figure 2). This is because "increase in flooding" is classified in the disaster sector and "exacerbation of PTSD and other mental disorders" is classified in the health sector, and their interconnection only appears in the sector-specific figures of the disaster and health sectors.

Another note of caution is that the size of a risk item icon reflects solely the number of associated interconnections; it does not necessarily indicate the importance or the magnitude of the risk. Furthermore, the interconnections have been extracted from academic research papers and should be interpreted accordingly. For example, the small number of interconnections related to the human system does not necessarily suggest that the human system is disconnected in reality. A more plausible interpretation is that there are fewer relevant studies currently available in this area relative to the number of studies dealing with other systems. Alternatively, this could simply be related to the nature of our literature survey, which depended

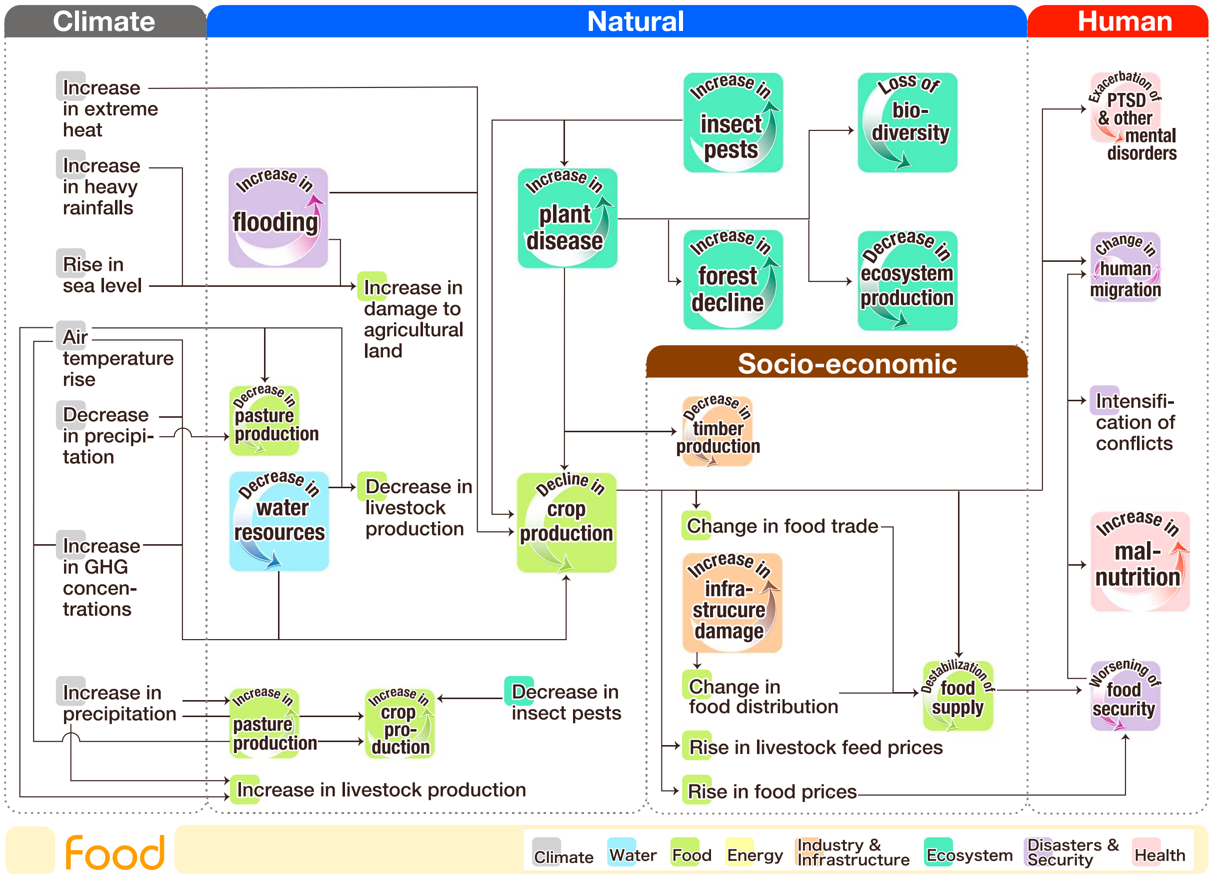

Figure 4. Flowchart of climate risk interconnections related to the food sector. The climatic drivers are allocated in the far left column. The risk terms of the sectors related to the natural and socioeconomic systems (upper rectangle in Figure 1) are placed in the middle column (blue and brown). The risk terms related to human life (lower rectangle in Figure 1) are allocated in the far right column. Causal links of the network flowchart (Figure 4) is the same as those of the corresponding network map (Figure 2).

ultimately on the expertise of our project members (Table S1). Future research using a more objective text mining technique to conduct the search would be useful.

3. Results

3.1. Climate Risk Interconnections Across Sectors

The cause–effect relationships between sectors are presented in Figure 1. As described in Figure 1, climate risks are connected across various sectors. The risks in each sector are caused directly by changes in the climate system (arrows connecting "climate" and other nodes) as well as by risks in other sectors. Climate drivers tend to be a cause of intersector risk interconnections (large orange pie inside the node), and most sectors tend to be both a cause and effect of intersector linkage (orange/blue pie). The health sector has the largest proportion of intersector effects (blue pie), indicating that this sector tends to be the end of the causal relationships in our analysis.

As explained in section 2.1, risk terms related to ecosystem services (e.g., MA 2005), whose potential amount is affected by the state of ecosystems, are included in the sectors such as food, water, industry, and energy as well as ecosystems. With this treatment, impacts of ecosystem on societal system via ecosystem service provision in the coupled social-ecological systems concept (Nassl & Löffler, 2015) are considered.

Figure 1 indicates an overall structure of climate risk interconnections: Changes in the climate system impact the natural and socioeconomic systems, ultimately influencing human security, health, and well-being. Figure 1 also shows the definition of natural and socioeconomic systems (upper rectangle, water, food, energy, industry, and infrastructure and ecosystem sectors), and the human system (lower rectangle, disaster, security, and health sector).

3.2. Network Maps and Flowcharts of Climate Risk Interconnections

The network map of food sector is shown in Figure 2. All the other sector-specific risk maps and flowcharts are shown in Figures S4–S10 in the supporting information. Tracing individual risk interconnections in the network map gives an insight into the overall features of risk propagation. To illustrate, we extract the direct and indirect relationships connected to the term “decline in crop production” from the network map of food sector (Figure 2). We selected these relationships because the decline in crop production is caused by various terms and can lead to a range of impacts. In Figure 3, the interconnections related to the term decline in crop production are shown in the four panels, and each panel represents the causal links concerning the climate, natural, socioeconomic, and human systems. The four panels in Figure 3 are also shown in the form of PowerPoint files (supporting information).

As shown in Figure 3a, changes in climate system can cause a decline in crop production. As related climate drivers, there are air temperature rise, an increase in extreme heat, and a decrease in precipitation (Porter et al., 2014). In addition, impacts on water and ecosystem sector (i.e., a decrease in water resources; Kovats et al., 2014) and an increase in insect pests and plant disease (Porter et al., 2014) can induce a decline in crop production (Figure 3b).

Then, the changes in climate and natural systems can bring about changes in socioeconomic system, such as food trades, price, and supply. As shown in Figure 3c, a decline in crop production can disrupt the food trade, causing food prices to rise and destabilizing the food supply (Niang et al., 2014; Porter et al., 2014; Reisinger et al., 2014). About three quarters of global calorie production come from only several crops (wheat, rice, maize, soybean, sugar, potato, etc.) whose production is concentrated in a small number of countries (Challinor et al., 2017; West et al., 2014). Therefore, the food security of most countries is dependent on the global food trade and impacts on a few breadbasket areas can be a systematic risk with global impact (Puma et al., 2015).

Finally, these changes in climate, natural, and socioeconomic systems can lead to impacts on human security and health (Figure 3d). Violent conflicts between individuals or groups can arise because of a variety of factors including those related to climate change, such as worsening of food security (FAO 2010; Porter et al., 2014) and poverty and economic shocks (Adger et al., 2014; Olsson et al., 2014). On the other hand, climate change impacts on agricultural productivity can lead to changes in migration flows; for example, drought can lead to an increase in migration (Adger et al., 2014). Kniveton et al. (2012) modeled migration movements from the 1980s in Burkina Faso and projected that decreased rainfall in the future would increase migration from rural areas.

As for possible impacts on human health, worsening of food security can result in nutrition-related diseases, especially among children (Smith et al., 2014; United Nations Office for the Coordination of Humanitarian Affairs, 2008). In addition, as demonstrated in the case of farmers in Australia in 2008, impacts on agricultural productivity caused by prolonged drought have exacerbated the PTSD and other mental disorders and increased incidence of suicide, because of the financial stress imposed to farmers (Alston & Kent, 2008; Hanigan et al., 2012).

In summary, changes in climate system impact natural and socioeconomic systems, ultimately influencing human security and health as exemplified in Figure 3. Based on this understanding of overall structure for the climate risk transmissions, we present network flowchart by reallocating the nodes and icons according to the natural, socioeconomic, and human systems (Figure 4).

The arrows in the network maps have various orientations (as in Figure 2). In contrast, by assigning the climate system to the upstream (far left) position and the human system to the downstream or endpoint (far right) position in the flowchart, with the natural and socioeconomic systems in between, the direction of the arrows is essentially from left to right, which enables us to readily grasp the structure of the climate risk cascades (Figure 4).

As discussed above, the decline in crop production is caused by, and brings about, various risks, locating it in the center of the risk cascade. The climate drivers shown at the far left of the figure are direct causes of the decline in crop production, which is also caused by changes in natural system such as decrease in water resources (Porter et al., 2014). The term decline in crop production affects elements of the socioeconomic system such as food trade, price, and distribution (Porter et al., 2014), leading to issues in the human system such as conflict, migration, and malnutrition (Adger et al., 2014; Hsiang et al., 2013; Smith et al., 2014).

4. Discussion

4.1. Implications for Climate Change Impact Research

Our visualization shows that climate risks are interconnected across a wide variety of sectors, and a particular risk is caused by multiple direct and indirect pathways. Taking "increase in malnutrition" as an example of endpoint, this risk term is affected through the food security related to changes in water resources, ecosystems, flood, and infrastructure (Figure 3), as well as through the impacts on health sector such as diarrhea and infections (Figure S10). Information on multiple pathways leading to a specific risk is important for risk assessments (International Risk Governance Council, 2005).

In addition, current estimates of the globally aggregated total costs of climate impacts differ substantially across studies, reflecting the fact that each study addresses different kinds of impacts under a variety of assumptions (Arent et al., 2014). For instance, damage functions (e.g., Anthoff & Tol, 2013; Hope, 2013), which are used to estimate the social costs of carbon (Pizer et al., 2014), are typically formulated as a function of the surface air temperature or greenhouse gas concentration without accounting directly for other drivers and intermediate risks. Our sector-specific risk diagrams may be useful for identifying unaccounted for risks and interconnections that should be included in future impact studies.

4.2. Useful Tool for Climate Risk Communication

Our visualization products put together climate risks and their interrelations as comprehensively as possible. To provide the public with climate-related risks in a digestible manner so that they can effectively cope with risks (International Risk Governance Council, 2005), we made efforts to organize such information systematically and to arrange the risk maps and flowcharts visually appealing.

In order to test the usability of our approach with potential users, we presented the network maps and flowcharts (Figures 2–4 and S4–S10) to members of the Dialogue and Co-production Office at the National Institute for Environmental Studies, all of whom are communication specialists whose responsibility is to deliver the outcomes of environmental research to the general publics and promote dialogue between researchers and stakeholders. We explained the purposes and scopes of the literature review and our visualization approach and discussed the findings from our visualizations. Feedback from the group can be summarized as follows:

Portraying all sector-specific relationships in a single figure (e.g., Figure 2) made it difficult to understand. However, selecting a particular relationship as an example (Figure 3) was helpful in clarifying the risk interconnections.

Illustrating the course of cascading risk using the layered structure of natural, socioeconomic, and human systems, as shown in Figure 3 (especially in the PowerPoint format; supporting information), can effectively convey the overall picture of climate risks.

Narrative examples of risk interconnections in the past (e.g., food security and conflict) can promote understanding for the linkages between climate risks. Information on linkages provided a better understanding of a particular risk.

The tested group also pointed out the following likely benefits and potential issues associated with the actual engagement with stakeholders using our visualization products: our visualizations may help stakeholders understand the big picture of climate risks. Stakeholders may use the visualizations as a guide to prepare for possible future impacts related to their particular field of activity.

Should stakeholders wish to produce a countermeasure, additional and more detailed information would be required, including the magnitude of impacts, the likelihood of occurrence, and reliability. For that purpose, an interactive system by which users can obtain the necessary information will be needed.

The public's perception of climate risk plays a central role in its willingness to engage the issue (Moser & Dilling, 2011; Swim et al., 2009). One of the challenges of communicating the risks of climate change is that people feel distant from its impacts (Moser, 2010). Simplifying the ways in which climate risk information is delivered is a necessary step in enhancing the public's understanding of the relationship between apparently distant climate impacts and their everyday lives. Effectively communicating the cascading effects of climate risk and their adverse impacts in an area like food production (Challinor et al., 2016) can change the public perception by showing that these impacts are neither distant nor disconnected. Furthermore, as discussed in UKCCRA2, knowledge of the various cause–effect risk interconnections can contribute greatly to the coordination of climate policies (Challinor et al., 2017).

5. Conclusions

Our visualization approach aims to comprehensively map out the impacts and consequences of climate change. Based on our visualizations, we clarified how various climate risks can affect multiple aspects of our lives and help elucidate the far-reaching impacts of climate change. Our study revealed a broad picture of climate change impacts, showing how changes in temperature and precipitation affect the natural and socioeconomic systems, ultimately influencing human security, health, and well-being. Our climate risk network diagrams may serve as a useful tool to foster a greater public understanding of what climate change can mean to society.

In this study, the climate risk items and cause–effect databases were generated by members of the research project on climate risk assessment (ICA-RUS 2012). With more researchers in a broader range of fields involved, the comprehensiveness of our databases can be improved. In addition, our selection of risk interconnections and the extent or boundary of activity that each project member oversaw was dependent on the judgment of the participating project members. Increased objectivity in the selection process may be achieved by employing a more systematic approach—one that establishes specific criteria for selection.

Furthermore, visualizing risk information along with the various climate risk interconnections is not an easy task using the type of static graphics. For the purpose of improved climate risk communication, several studies investigated the effectiveness of interactive visualization tools (Herring et al., 2016; Johansson et al., 2017; Koy et al., 2014), showing that an interactive visualization tool can have a strong effect on perceived reality of climate change. Interactive ways to present climate risk maps and flowcharts may further improve the usefulness of our approach to public engagement, as suggested by the responses we received from the group of potential users described above.

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