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Abrupt climate change: Exploring the implications of a wild card

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ABSTRACT

Anthropogenic climate change has been gradual to date, but if climate tipping points are crossed the pace of change could accelerate significantly. This study explores possible implications of abrupt climate change, with a partial focus on implications for forestry. We used the Implications Wheel® participatory futures method to identify and evaluate direct and indirect, positive and negative implications of rapid change in the climate system. A large number of possible implications were generated, including a wide range of social, economic, and ecological costs and benefits. Participants identified many "likely strong negative" implications that were scored as both highly likely and strongly negative. A key conclusion of this study is the importance of developing strategies to increase social and ecological resilience given the likelihood of highly disruptive impacts of abrupt climate change. A second conclusion is the need to identify early warning signals for abrupt climate change and closely monitor those signals. Finally, the fundamental uncertainty about abrupt climate change suggests the importance of futures research that taps into creativity and imagination. Our inaction in the face of climate change has been characterized as a failure of imagination, an inability to envision a different and sustainable world, and so futures thinking and methods that encourage creative thinking have an important role in addressing the "inevitable surprise" of abrupt climate change.

1. Introduction

Climate change has been viewed as a quintessential example of a slow environmental threat with enormous implications for the future (Olson & Rejeski, 2017). Over the past 50 years, the average increase in global temperatures has been just 0.17 degrees C per decade (NOAA National Centers for Environmental Information, 2015), slowly increasing with the steady rise in atmospheric carbon dioxide. The impacts of climate change have unfolded gradually so far and are expected to continue to develop over a time frame of many decades or even centuries. But what if one or several climate tipping points are crossed and the pace of change accelerates abruptly? Abrupt changes in the climatic system have occurred often in the past. For example, analysis of Greenland ice core records have revealed more than 20 episodes of sudden and intense climate warming in the paleoclimatic record (Alley, 2014). The landmark US National Research Council report on abrupt climate change characterized future abrupt changes in the climate as "inevitable surprises" (National Research Council, 2002).

The vast majority of research on climate change and its implications for social-ecological systems has focused on gradual changes in the climate (Alley, 2004). A notable exception was the highly influential scenario on abrupt climate change by Schwartz and Randall

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(2003). This study was commissioned by the US Department of Defense to explore potential consequences of large-scale climate disruption, especially implications for national security. The report focused on a shutdown of the Atlantic thermohaline circulation as a plausible tipping point for abrupt climate change. Significant media interest was generated by the report but sensationalized media coverage may have made it too controversial for Department of Defense planners to pursue (Shearer, 2005). Nevertheless, as Schwartz later observed, the report "… made people think about what happens when change is so rapid that human systems have a hard time adapting" (Schwartz, 2011, p. 20).

This study explores possible implications of abrupt climate change, with a partial focus on implications for forestry. While Lenton et al. (2019) and others have called for immediate and rigorous action due to the climate emergency and possibility of abrupt climate change, launching that action will require an elaboration of the climatic consequences of tipping points and their social and economic implications. Futures exercises to identify and analyze the indirect, interrelated, and complex implications of abrupt climate change may be conducted in various sectors to foster a more anticipatory, action-oriented mindset.

Our focus on the implications of abrupt climate change for forestry is due to several factors. First, ecosystems such as mature forests – characterized by a limited capacity to adapt to rapid change due to the immobility and long growing periods of trees – are likely to be especially vulnerable to abrupt climate change (Alley et al., 2003). Second, the world's forests play an important part in mitigating climate change through their role in sequestering atmospheric carbon dioxide (Bastin et al., 2019). Finally, forest dieback in the vast Amazon and boreal forests are a possible tipping point for abrupt climate change (Lenton et al., 2008).

We used a participatory futures research method called the Implications Wheel®, a variation of the futures wheel (Bengston, 2016), to identify and evaluate direct and indirect, positive and negative implications of rapid change in the climate system. The methods of futures research are well-suited to examining abrupt climate change because of its high level of uncertainty relative to gradual climate change (Alley et al., 2003). Abrupt climate change "… occurs when a slow but steady force, such as global warming, moves a crucial component of the climate system past a point of no easy return. Crossing such a threshold triggers a sudden switch to a new state – much the way leaning over too far in a canoe suddenly dumps you in the lake…" (Alley, 2004: 68). This type of change is inherently more difficult to forecast than gradual change because it involves a shift to a new and unknown state in the system. The Intergovernmental Panel on Climate Change (IPCC) estimated the likelihood of a rapid and major disruption of climate in the next decades to century to be less than 10 percent (IPCC, 2007), making abrupt climate change a classic low likelihood, high impact wild card event.

The following section defines abrupt climate change and identifies key tipping points that could trigger it. This is followed by a description of the Implications Wheel method and a discussion of the main findings of our exercise. A concluding section outlines the use of the findings for increasing resilience in social-ecological systems and highlights other strategies to prepare for the wide-ranging and surprising implications of abrupt climate change.

2. Abrupt climate change

Abrupt climate change, also called rapid climate change, involves significant shifts in climate on the scale of years to decades, in contrast to gradual climate changes that unfold over time spans of many decades or even centuries. The 2002 National Research Council report on abrupt climate change defined it in technical terms as follows: "… an abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause" (National Research Council, 2002, p. 14). In the past, the triggers that have forced climate change have been nonanthropogenic, such as major volcanic eruptions and changes in the earth's orbit around the sun (i.e., the Milankovitch cycles). Today, scientists are concerned that the human-caused increase in atmospheric carbon dioxide and resultant gradual global warming could trigger a sudden switch to a new and persistent state in the climate system (IPCC, 2007; National Research Council, 2013).

More recent definitions of abrupt climate change have been broader, encompassing both abrupt changes in the climate system and abrupt *impacts* in biophysical and human systems triggered by gradual climate change (National Research Council, 2013). An important characteristic of these abrupt changes and abrupt impacts is that they occur faster than anticipated, creating a challenge for proactive strategies.

The likelihood of future abrupt climate change is unknown, but there is abundant scientific evidence that Earth's climate has changed suddenly many times in the past. Dramatic climatic shifts have been revealed from ice and sediment cores and other paleoclimatic records in which significant changes occurred within a few decades or even a few years (Alley, 2014; Rahmstorf, 2010). For example, the "4.2 kiloyear event" was a period of intense aridity in many regions across the globe and unusually wet conditions in other regions that happened about 4200 years BP (deMenocal, 2001; Wang, Wang, Chen, Sun, & Wang, 2016). This severe and rapid climate event is hypothesized to have caused or contributed to the collapse of several ancient civilizations.

Tipping point and tipping element are key terms related to abrupt climate change. Lenton et al. (2008) define tipping point as "… a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system" (p. 1786). Tipping elements are defined as "… large-scale components of the Earth system that may pass a tipping point" (p. 1786). Potential policy-relevant tipping elements in the climate system – those that may be affected by human activities and therefore could be germane to policy – and their associated tipping points include the following:

- **Atlantic Thermohaline Circulation (THC):** Ocean currents are an important moderating force in the climate system. Disruption of the Atlantic THC has been linked to past abrupt climate changes (Clark, Pisias, Stocker, & Weaver, 2002) and may occur when a massive amount of fresh water is released due to melting of the Greenland ice sheet (Lenton, 2012). Recent evidence indicates that circulation of the Atlantic Ocean has slowed by about 15 percent in the past few decades (Caesar, Rahmstorf, Robinson, Feulner, &

Saba, 2018). A significant slowdown or complete shutdown of the Atlantic THC would constitute crossing a climate threshold with profound consequences.

- **Greenland and West Antarctic Ice Sheets:** The Greenland and Antarctic ice sheets are the planet's largest ice masses. Melting of the Greenland ice sheet and West Antarctic ice sliding into the ocean have become increasingly important contributors to accelerating sea level rise in recent decades (Shepherd et al., 2018). Recent research has found that loss of ice from these ice sheets will accelerate and become irreversible if global temperatures increase more than a modest threshold of 1.5–2.0 degrees C above pre-industrial levels (Pattyn et al., 2018). Satellite studies of the Amundsen Sea area of West Antarctica have revealed ice sheet retreat consistent with emergent collapse (Vaughan, 2008).
- **Amazon rainforest and boreal forest:** Forests play an important role in the global climate system (Bastin et al., 2019). Dieback, or large-scale mortality, of the vast Amazon rainforest and the northern boreal forest have been predicted to occur under approximately 3 degrees C of global warming, although limitations in modelling and understanding of these systems make the precise temperature highly uncertain (Lenton et al., 2008 and studies cited therein). The impacts of large-scale loss of forests on the carbon cycle, water cycle, global climate system, and socioeconomic systems would be significant (Lapola et al., 2018).
- **Arctic permafrost:** The Arctic has been warming at twice the rate as the rest of the planet in recent decades (Osborne et al., 2018). This has raised concern about thawing permafrost and the release of significant amounts of carbon dioxide and methane into the atmosphere, resulting in an accelerated pace of climate change or even triggering an abrupt shift in the climate system. Methane is an especially potent greenhouse gas – many times more potent as a heat-trapping gas than carbon dioxide. Recent research funded by NASA has found that a little known process of "abrupt thawing" could speed up the expected gradual thawing of Arctic permafrost and rapidly release large amounts of methane (Anthony et al., 2018).
- **Arctic sea ice:** Melting sea-ice exposes a darker ocean surface, which absorbs more solar radiation and accelerates warming – a positive feedback cycle. The extent of summer sea-ice in the Arctic has declined significantly in recent decades and winter sea-ice is also declining (Lenton, 2012). The observed decline has been greater than all of the IPCC model projections (Stroeve, Holland, Meier, Scambos, & Serreze, 2007). In addition to Arctic sea-ice declining in area, the ice has thinned markedly (Wadhams, 2012).

A host of additional large-scale and regional tipping elements (and their associated tipping points) have been identified, including the El Nino-Southern Oscillation, the Indian summer monsoon, the Sahara/Sahel and West African monsoon, the release of marine methane hydrates, and many others (Lenton et al., 2008, 2019). If these or unknown tipping events force the climate system to cross a threshold into a new state, the effects would be wide-ranging and largely unanticipated. The impacts of abrupt climate change would likely be so rapid and surprising that human and natural systems would have difficulty adapting to them (National Research Council, 2002). There would be ecological impacts, but also unexpected social, cultural, economic, political, security, health, and other impacts (Mora et al., 2018; National Research Council, 2013). These sweeping and interrelated impacts could have serious consequences for the stability of social-ecological systems.

3. Method: The Implications Wheel®

The Implications Wheel is a structured group technique designed to identify and evaluate possible direct and higher-order consequences of change (Barker, 2011; Schreier, 2005). A refined version of the futures wheel (Glenn, 2009), the Implications Wheel was developed by futurist Joel Barker. The name stems from the wheel-like structure that emerges as the group process proceeds: A significant change of interest is placed in the center like the hub of a wheel, and first-, second-, and third-order implications of the change are generated by participants and emanate outward from the center like the spokes of a wheel. The process facilitates "cascade thinking," described by Barker and Kenny (2011:2) as "how one event or implication leads to multiple possibilities, each of which in turn leads to additional possibilities." Cascade thinking helps planners and decision makers proactively consider a range of potential long-term, higher-order effects of change in order to prepare for it. Published Implications Wheel exercises have covered a wide range of topics, including studies identifying the implications of redesigning teacher education (Middleton & Prince, 2011), proposed church policies (Gebhard, Meyer, & Barker, 2006), a vision statement for a professional society (Fogarty, Radcliffe, & Campbell, 2006), and a major trend affecting forests (Bengston, Dockry, & Shifley 2018).

An Implications Wheel exercise can be carried out in-person, with participants together in the same place at the same time, or online and asynchronously using the Implications Wheel cloud-based software (https://www.implicationswheel.com). Our exercise was carried out in-person as a workshop at a forestry conference in Duluth, Minnesota, USA in July 2019. A total of 32 participants took part in the exercise: 18 male and 14 female, just over half from the USA and the rest from nine other countries, ages ranged from the 20 s through 60 s with a modal value of 50 s, and 69 percent of participants had a highest degree of PhD. The expertise of participants was wide-ranging and included many different forestry and natural resource related degrees as well as economics, policy, and sociology.

The change at the center of our Implications Wheel exercise was: "Abrupt climate change occurs: Tipping events trigger abrupt changes in the climate system." This center issue was identified in part through a horizon scanning system (Hines, Bengston, & Dockry, 2019). Many scanning hits related to abrupt climate change were posted in the scanning database and it was decided that the potential high-impact consequences of this change warranted in-depth exploration.

Prior to conducting the Implications Wheel exercise with the full group of participants, the research team used an adaptation of the "6-3-5" brainwriting method (Rhorbach, 1969) with six individuals from diverse disciplines and backgrounds to identify a meaningful and balanced set of five first-order implications. Identification of a broad-ranging set of first-order implications is an important step in setting up an Implications Wheel exercise – a narrow set of first-orders would limit the generation of higher-order implications. The

6-3-5 brainwriting method is a silent collaboration method involving six people around a table writing three ideas on a given topic, after which each of them passes the paper to the next person in the circle who builds on the first ideas or adds new ones. This passing on and idea elaboration is repeated five times, until the papers have made a full circle and overall assessment of the ideas generated can take place.

In this study, the modified 6-3-5 method involved a six-person table and six five-minute turns as follows: (1) After a briefing on abrupt climate change, each participant was asked to generate two direct implications of abrupt climate change on a sheet of paper, (2) the papers were passed clockwise and participants each generated two more implications, (3) the preceding step was repeated and participants generated two more implications, (4) the papers were passed again and participants had the opportunity to comment or challenge any of the six proposed implications on their paper, (5) the papers were passed again and participants had the opportunity to comment on or challenge a new set of six proposed implications, (6) participants rated the implications at hand, assigning a score of 100 to the most influential one and proportionately less to the others relative to the first. During the implication identification rounds, participants were reminded to think broadly, referring to the STEEP domain categories. Scoring was used as an indicator of participants' perceptions of importance.

The modified 6-3-5 process generated a total of 36 possible direct or first-orders, but many of them were not direct implications of the center, were ambiguous, or were duplicates. After assessing the group output, a set of five broad and well-balanced first-orders were selected for exploration. Only one of the five is specifically focused on forests:

- People accept climate change as a reality: There is a widespread and rapid shift in public beliefs about climate change.
- Climate disturbance events increase in frequency and intensity around the world (e.g., wildfires, droughts, floods, etc.).
- Locally serious crop failures increase in many regions due to changes in agro-climate conditions.
- Large-scale forest mortality occurs in some regions.
- Strong pressure on governments at all scales to restructure their economies and rapidly transition to carbon-negative societies.

Given a center and a set of first-order implications, an Implications Wheel exercise consists of two rounds of identifying higher-order (second- and third-order) implications and one scoring round. At the beginning of the exercise, participants were briefed about the central issue and given instructions about how to generate implications (i.e., a set of rules that help ensure useful implications and timely completion of the exercise). Participants were then divided into groups of four, with each group given one first-order implication to focus on.[1] The first round began by the facilitator posing the question: "If this first-order implication occurs, what might happen next?" Participants generated a set of possible second-order implications for each first-order. When identifying second-order implications, participants were instructed to assume that the preceding first-order implication is occurring and will continue, and to generate implications that are a direct consequence of the first-order with no noteworthy intervening events. Participants were encouraged to think broadly and to identify positive and negative, high and low probability implications. The goal was to generate a wide-ranging set of possible implications and not inhibit creative, outside-the-box thinking. After the first brainstorming round was completed, the process was repeated to identify a set of third-order implications for each second-order.

Following identification of implications, participants scored each first-, second-, and third-order for two criteria: desirability and likelihood. Scoring highlights the most significant implications and points out potential opportunities and pitfalls (Schreier, 2005). Each implication was scored on an 11-point desirability scale from +5 (highly positive) to −5 (highly negative), and on a 9-point likelihood scale from 1 (highly unlikely) to 9 (highly likely). Desirability scoring was carried out from the point of view of small-scale forestry, since this exercise was carried out at a conference on small-scale or family forestry. Consensus scores were determined through discussion in each small group. If an individual disagreed with the group's score, that person's score was also recorded as a "minority report."

In addition to the standard desirability scores, groups could also assign special scores to implications they considered to have highly significant impacts. An implication thought to have an extraordinarily positive impact is termed a "triumph" and is assigned a score of +50 by participants; an implication considered to have extraordinarily negative consequence it is referred to as a "catastrophe" and was scored −50.

4. Findings

4.1. Number of implications

Starting with the five pre-selected first-order implications, our participants generated 41 second-orders and 178 third-orders (Fig. 1), for a total of 224 possible implications of abrupt climate change. Third-order implications significantly outnumber lower-level implications due to the structure and process of the Implications Wheel: As the process moves outward from the center, the number of implications grows exponentially. This shifts the focus of thinking from immediate and direct implications of the central issue to potential longer-term and indirect implications. Without this structure, most people focus on the immediate consequences of change. Unstructured brainstorming about the possible implications of change has been found to produce an overwhelming majority of first-order implications, a handful of second-orders, and almost no third-orders (Schreier, 2011), exactly the opposite of what is shown

[1] Three of the first-orders had two groups that focused on them. There were eight groups in total, so three of the five first-orders were covered by multiple groups.

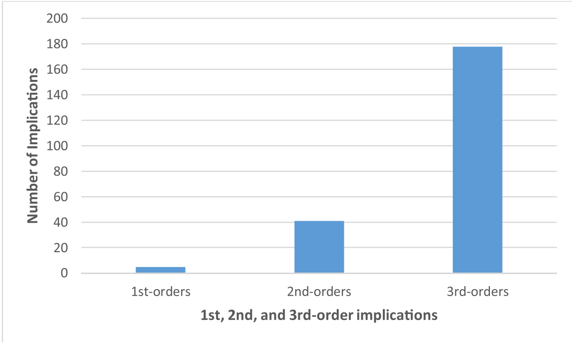

Fig. 1. Number of first-, second-, and third-order implications generated.

in Fig. 1.

4.2. Positive and negative implications

Climate change – and especially abrupt climate change – is widely viewed as wholly negative or catastrophic. But out of 224 total implications, our participants scored less than half as negative (44 percent), 38 percent as positive, and 18 percent as neutral from the perspective of small-scale forestry.[2] The fact that 56 percent of the implications in this study were scored as positive or neutral suggests a principle for thinking about the future: What may appear to be an unambiguously negative future development could result in unexpected positive consequences and opportunities in the long-term. Conversely, a trend or development that is widely viewed as positive can produce unexpected negative consequences and challenges. The following chain of implications illustrates positive higher-order implications arising from a negative first-order:

First-order: “Climate disturbance events increase in frequency and intensity around the world (wildfire, drought, floods, etc.)” (Scored as -5 desirability, 9 likelihood), [8][3]

Second-order: “Humans innovate and adapt at an increasing rate” (+5 desirability, 5 likelihood), [8.2]

Third-order: “People learn to harness floods, fire, drought to our benefit” (+5 desirability, 5 likelihood), [8.2.3]

4.3. Highly significant implications

Implications with special significance for planning and policy include “likely strong negatives” and “unlikely strong positives.” Likely strong negatives are implications that were scored as both highly likely (7, 8 or 9 on the 9-point likelihood scale) and strongly negative (-4 or -5 on the 11-point desirability scale). Likely strong negative implications call for policies, management actions, or other interventions to decrease their likelihood of occurring, lessen their undesirable effects, or both. Unlikely strong positives were scored as both unlikely (1, 2 or 3 likelihood) and strongly positive (+4 or +5 desirability). Unlikely strong positives require interventions to increase their chances of occurring.

Participants’ scored a total of 44 implications as likely strong negatives and only 3 as unlikely strong positives. Examples of likely strong negatives and their chain of preceding implications include:

First-order: “Strong pressure on governments at all scales to restructure their economies and rapidly transition to carbon-negative societies” (+4 desirability, 7 likelihood), [1]

Second-order: “In order to achieve this rapidly, more authoritarian governments would arise and people’s freedoms and rights would be diminished” (**Likely strong negative**: -4 desirability, 7 likelihood), [1.1]

First-order: “Large-scale forest mortality occurs in some regions” (**Likely strong negative**: -5 desirability, 7 likelihood), [3]

Second-order: “Timber and forest product market disruptions” (-3 desirability, 9 likelihood), [3.3]

Third-order: “In the long-term, shortage and higher prices for raw materials” (**Likely strong negative**: -5 desirability, 9 likelihood), [3.3.2]

[2] Neutral scores included a narrow range around zero on the 11-point desirability scale, i.e., group consensus scores of −1, 0, and +1 were counted as neutral.

[3] Numbers inside square brackets following an implication refer to the specific implication in the Supplemental Materials. A one-digit number references a first-order from a particular group (numbered 1−8 for the eight groups), and two- and three-digit numbers refer to specific second- or third-order implications from a particular group.

First-order: “People accept climate change as a reality: There is a widespread and rapid shift in public beliefs about climate change” (+4 desirability, 6 likelihood), [7]

Second-order: “Massive increase in government spending on coastal projects to protect against sea-level rise” (+1 desirability, 7 likelihood), [7.5]

Third-order: “Money wasted on impossible projects and doomed communities” (**Likely strong negative**: -4 desirability, 8 likelihood), [7.5.2]

A next step for using these likely strong negative implications in policy and planning would be to identify specific actions needed to address these undesirable but plausible developments, if abrupt climate change occurs and the implications begin to emerge.

Examples of unlikely strong positive implications and their chain of preceding implications include the following:

First-order: “Strong pressure on governments at all scales to restructure their economies and rapidly transition to carbon-negative societies” (+4 desirability, 7 likelihood), [1]

Second-order: “Taxes go up to support research and innovation in carbon negative technologies” (0 desirability, 7 likelihood), [1.5]

Third-order: “Improved efficiency in government allocation of funding” (**Unlikely strong positive:** +5 desirability, 1 likelihood), [1.5.2]

First-order: “Strong pressure on governments at all scales to restructure their economies and rapidly transition to carbon-negative societies” (+4 desirability, 7 likelihood), [2]

Second-order: “Rapid movement away from petroleum-based products” (+5 desirability, 8 likelihood), [2.2]

Third-order: “Increase in local production of all goods” (**Unlikely strong positive:** +4 desirability, 2 likelihood), [2.2.1]

The fact that just three unlikely strong positive implications were generated by our participants is surprising given that 38 percent of all implications were scored as positive. Participants focused on the more likely or expected positive implications of abrupt climate change, rather than unlikely positive implications.

4.4. Major emergent themes

Several broad themes emerged from the many second- and third-order implications of abrupt climate change. These are analogous to the themes or issues that typically emerge from analysis of focus group or in-depth interview transcripts. The “open coding” method of qualitative content analysis was used to identify major themes. Briefly, this method involved a process of repeated and careful reading of the implications, developing an outline of recurring themes, and cross-referencing each theme back to the original implication. See Strauss and Corbin (1998) for details on the open coding method.

The main themes appeared repeatedly and in different contexts within the structure of the Implications Wheel, i.e., each of the major themes arose from multiple first- and second-order implications. This lends support to the validity and importance of these themes, similar to group-to-group validation in focus groups (Morgan, 1997).[4] The most common themes arising out of the center “Abrupt climate change occurs: Tipping events trigger abrupt changes in the climate system” are shown in Fig. 2. An important finding was that the positive theme of “increased innovation” was mentioned most often, for example:

- “New technologies developed to improve agriculture and forestry,” [5.3.4]
- “New training programs for farmers are introduced” related to the introduction of new, more viable crops, [6.5.1]
- “Greater adoption of climate-adapted species and varieties,” [7.3.3]

Twenty one of the twenty eight implications expressing “increased innovation” were third-orders, suggesting the importance of looking well beyond direct implications to see how positive outcomes can arise from an undesirable event such as abrupt climate change.

Other frequently expressed emergent themes included economic, ecological, and social costs – not surprisingly – but also benefits or positive developments related to each of these domains as well. For example,

- Ecological Benefits: “Support for massive reforestation in appropriate geographic areas” [1.5.3], “More biodiversity leads to greater resiliency” [5.2.2]
- Social Benefits: “Increased awareness of the impact of climate change” [4.5.1], “Greater resilience in communities (better able to withstand storms, higher sea levels)” [7.5.4]
- Economic Benefits: “Diversification of income sources [for forest owners]” [3.3.3], “More income and jobs for local communities” [5.5.1]

[4] In the analysis of focus group transcripts, group-to-group validation “… means that whenever a topic comes up, it generates a consistent level of energy among a consistent proportion of the participants across nearly all the groups” (Morgan, 1997, p. 63).

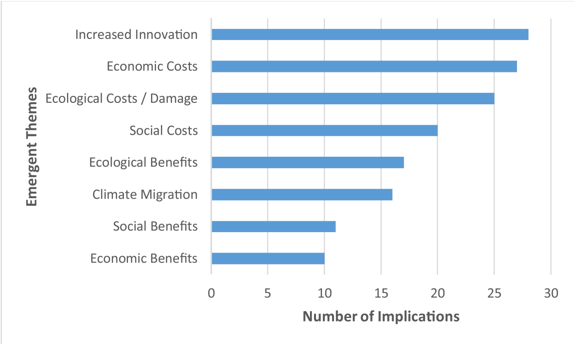

Fig. 2. Major emergent themes.

The theme “climate migration” shown in Fig. 2 was a mix of positive, neutral, and negative implications, although half of the migration-related implications were scored negative. In addition to expected implications such as increased migration from wildfire-prone areas and migration to less climate-sensitive areas, an outside-the-box migration implication was “Human settlement of other planets and the Moon” [8.2.1].

4.5. Triumphs and catastrophes

Triumphs and catastrophes are implications deemed to have extraordinarily positive or negative effects and are scored as +50 or -50. Implications Wheel exercises typically produce a few of these exceptionally high impact implications. In this study, five of the 224 implications were scored by participants as catastrophes and one was scored as a triumph. One of the catastrophes involved wide-spread loss of ecosystem services following massive and intense wildfires:

> *Second-order:* “Significant increase in catastrophic fires in regions impacted by forest mortality,” [3.2]
>
> *Third-order:* “Almost all ecosystem services are destroyed, (**Catastrophe:** -50, 7), [3.2.2]

The other catastrophes directly included loss of human life, in some cases significant loss, due to a “significant increase in spread of contagious disease: Global pandemic” [2.5.2], “significant loss of infrastructure, homes, and human lives” [3.2.5], “Famine and increased human mortality” [6.2], and “global nuclear war” [1.3.4].

Although it is a big leap from abrupt climate change to “global nuclear war,” it is possible and the Implications Wheel is intended to explore possible implications of change, even low-probability implications. The one triumph scored by participants was also a low-probability event:

> *Second-order:* Widespread recognition that we all need to work together toward a common goal (a carbon-negative society),” [2.4]
>
> *Third-order:* “World peace” (**Triumph**: +50, 2), [2.4.1]

Once again, it is a big step from “widespread recognition that we all need to work together toward a common goal” to “world peace.” But the idea that a major and widely accepted unifying goal can bring people together and have a transformative effect on society is plausible.

5. Conclusions and implications

This study uncovered a large number of possible implications of what could be a highly disruptive wild card. Given the many important consequences of abrupt climate change – especially the many “likely strong negative” implications and five “catastrophes” identified by our participants – this issue is worthy of much more scrutiny from climate scientists, social scientists, policy makers, and others who have overwhelmingly focused on the effects of gradual climate change.

Of course, not every possible future problem and opportunity can be identified through Implications Wheel exercises or other futures methods. The future of complex social-ecological systems holds unlimited potentials and surprises, and there is no way to know which of the many possible and plausible higher-order implications will be realized. But a strength of the Implications Wheel method is the sheer quantity of possibilities generated. Creativity research has found that the quantity of ideas is critical (Besant, 2016; Michalko, 2006). The large number of possible implications uncovered in an exercise such as ours increases the likelihood that insightful and novel ideas will be produced, from which the most important and policy-relevant can be identified through scoring and further analysis. Anticipating possibilities in advance can provide early indicators of the kinds of changes that may be coming or are needed, and can help planners, managers, and policy makers to be proactive and build barriers to undesirable change and bridges to facilitate positive change.

For example, many positive implications related to increased innovation emerged from this exercise (Fig. 2). Facilitating this positive change would require research managers and policy makers to proactively design and invest in appropriate research and development programs. Many negative implications related to possible economic costs of abrupt climate change were also identified (Fig. 2). Policies to prevent or minimize these undesirable impacts, such as investments in resilient infrastructure, require anticipating these costs well in advance and planning to avoid them.

Extensions of this research could produce additional foresight about the potential consequences of abrupt climate change. For example:

- Repeated Implications Wheel exercises with a greater diversity of participants would generate a wider range of implications with new insights.
- The large number of implications from repeated exercises could be used to develop full scenarios of abrupt climate change.
- Scoring the desirability of implications from the perspectives of additional stakeholders and interests (e.g., future generations, national security interests, and indigenous perspectives) would uncover further dimensions of the social consequences of abrupt climate change.

A key conclusion of this study is the importance of developing strategies to increase social and ecological resilience. Pervasive uncertainty about future abrupt climate change combined with a strong likelihood of highly disruptive impacts suggests the urgency of identifying options to improve resiliency and adaptability in social-ecological systems (Alley et al., 2003). Facilitating key stakeholders' comprehension of potential second- and third-order implications of abrupt climate change may catalyze new partnerships and strategic actions that lead to a tangible increase in resilience in social-ecological systems. In general, futures thinking and methods help us to expect the unexpected, thereby helping to build greater resilience of systems to surprise.

Another conclusion is the need to identify and closely monitor early warning signals of abrupt climate change. For example, Dakos et al. (2008) developed a method to detect slowing down of fluctuations in the state of a system, which is a signal for the climate system reaching a tipping point that could lead to rapid change. Recent evidence suggests that the Atlantic Thermohaline Circulation is slowing (Berwyn, 2018). Lenton et al. (2008) and National Research Council (2013) discuss the prospects for developing early warning systems for various climate tipping elements and abrupt change.

In addition to climate scientists monitoring early signals of abrupt change in the climate system, futures research methods could be used to identify and monitor early signals of abrupt climate-induced change in social, cultural, economic, and political systems. For example, many of the "highly significant implications" (based on their scores) identified in this study are indicators of possible changes that could be monitored through focused horizon scanning. In addition, wild card monitoring systems (e.g., Markley, 2011; Petersen & Steinmueller, 2009) could be used to track early signals of abrupt climate change and its many possible effects.

Finally, the fundamental uncertainty about future abrupt climate change – and all wild card events – suggests the importance of futures research methods such as the Implications Wheel and others that tap into creativity and imagination. In this sense, using futures methods widely in society is essentially a stakeholder educational activity, which helps individuals and collectives stretch their imaginations and achieve ownership and agency of the complex and wicked problems at hand. Amitav Ghosh (2017) has characterized our collective lack of action in the face of climate change as fundamentally a failure of imagination, an inability to imagine doing things differently, to envision a different and sustainable world. Futures thinking and methods that encourage creative thinking about the unthinkable have an important role in addressing the "inevitable surprise" of abrupt climate change.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.futures.2020.102641.

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