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Understanding Interdependent Climate Change Risks Using a Serious Game

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ABSTRACT: Anthropogenic climate change calls for rapid and enormous cuts in emissions of CO_2 and other greenhouse gases to mitigate future impacts. Even with these, however, many changes will continue to occur over the next 20–30 years adding to those already observed. Adaptation is crucial and urgent, but identifying strategies is complex and requires dialogue and cooperation among stakeholders, especially for infrastructure that exhibits interdependent risks in that failure in one type may impact others. A serious game was codeveloped with infrastructure operators to communicate climate projections and climate hazards to them; identify potential interdependencies, cascading impacts, cumulative effects, and vulnerability hot spots; and engage them to improve cooperation and enable a shared understanding of cross-cutting climate risks and interdependencies. In the game, players provide present-day infrastructure services in the Inverclyde district, Scotland, as they experience a plausible decade of 2050s weather characterized by a sequence of hazard events. This sequence was extracted from climate model projections to ensure scientific plausibility. The infrastructure operators were responsible for drinking water and gas supplies, road and rail transport, wastewater treatment, and civil infrastructure. When playing the game the participating U.K. infrastructure providers felt that although there were challenges, they could cope with 2050s climate change. None of the projected hazard events were anticipated to cause catastrophic impact cascades on infrastructure. The game was positively received, and the study suggests it is a useful tool to both communicate climate hazards and explore potential interdependent risks by bringing together stakeholders' individual expertise in an engaging way.

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S cotland's climate is changing. It is getting hotter, wetter, and sea level is rising (Kendon et al. 2019). Over the next 20–30 years climate change will intensify globally (Kirtman et al. 2013) and in Scotland (Murphy et al. 2018). This means not only that slow-onset changes will become more visible, but also that the return periods of extreme weather events will change further—such changes as are already having an impact on infrastructure in Scotland (e.g., Undorf et al. 2020). Even with a rapid transition to net-zero CO_2 emissions society will need to adapt (IPCC 2014). Identifying adaptation needs and developing adaptation strategies is a complex task, and the United Kingdom's Committee on Climate Change highlights the need to "address the important interdependencies between climate change risks and policy responses [...] to ensure relevant policies and activity are coordinated" (Committee on Climate Change 2017).

Infrastructure provides the physical and virtual support systems essential to sustaining societal living conditions (e.g., Aitsi-Selmi et al. 2015)—including energy, water, transport, and telecommunications. It is widely exposed to a variety of climate hazards[1] (e.g., Mora et al. 2018; Forzieri et al. 2018). Often individual infrastructure elements depend on other infrastructure, so impacts on one may cause impact on another—creating an impact cascade (e.g., Chapman et al. 2013). Responsibility for infrastructure is shared among different actors; in the United Kingdom, this includes government (United Kingdom and devolved), government agencies, local authorities, and state-owned and private companies. Failure to tackle cross-cutting risks may lead to "the true magnitude of risks and opportunities [being] underestimated because each tends to be considered in isolation but in practice will act in combination" (Adaptation Sub-Committee 2016).

[1] Here, we use the term "climate hazards" to mean weather- and climate-related hazards as, for example, Mora et al. (2018).

There is an urgent need for approaches that facilitate the sharing of expert understanding between infrastructure managers to enable them to, *together*, more effectively adapt to climate change. Adaptation must be informed by climate projections, but since meteorological expertise cannot be expected, these need to be translated into environmental risks (e.g., Sutton 2019) accessible to stakeholders with a range of technical expertise, and integrated with existing practice. Serious games are a promising approach to communicate climate hazards, identify the associated risks, and facilitate adaptation cooperation.

The benefits of using a serious game approach are being increasingly recognized in environmental contexts. A classic tool in international negotiations, game theory is applied to understand negotiation behavior for mitigation (e.g., Ward 1996; Hovi et al. 2015; Verendel et al. 2016; Caparrós 2016) and adaptation (Jeong et al. 2018; Li and Rus 2019; Papakonstantinou et al. 2019) with the aim to identify policy strategies (e.g., Vasconcelos et al. 2013) or scientific knowledge needs (Barrett and Dannenberg 2014) that increase the likelihood of successful cooperation. When empirically performed, these games can be conceptualized following Rodela et al. (2019) as *games used for research*. In contrast, *educational games* aim primarily at communicating knowledge, and *games as interventions* intend to transform behavior through social learning [e.g., Mendler de Suarez et al. 2012; Reckien and Eisenack 2013; Wu and Lee 2015; Parker et al. 2016; Chappin et al. 2017; Khoury et al. 2018; den Haan and van

der Voort 2018; Flood et al. 2018; International Federation of Red Cross and Red Crescent Societies (IFRC); IFRC 2019]. Further examples of the increased use of game approaches are entertainment (nonserious) board and video games with environmental content included in game mechanics (e.g., Firaxis Games 2016) or in game graphics (Abraham 2018) and the gamification of tools for behavior change (Beck et al. 2019; Zehir et al. 2019).

We report on using a serious game approach that combines aspects of education, research, and intervention games (Rodela et al. 2019). Our game (*Cascade: A Decade of Weather* or short *Cascade*) is designed to (i) communicate climate projections and climate hazards to infrastructure operators; (ii) identify potential interdependencies, cascading impacts, cumulative effects, and vulnerability hot spots; and (iii) engage infrastructure operators to improve cooperation and enable a shared understanding of cross-cutting climate risks and interdependencies. Codeveloping a game with stakeholders will likely add value to the game approach (e.g., Sušnik et al. 2018) and was a crucial part of our game development process. Unlike negotiation-based games, we do not gather information on the players' decisions as empirical data points, but instead learn from their discussions (Vieira Pak and Castillo Brieva 2010)—the research-relevant outcome of the game relies on the players' knowledge and expertise about infrastructure vulnerability and exposure.

The aim of the game *Cascade* is for players to provide present-day infrastructure services as they experience a plausible decade of 2050s weather. To provide the "real word" context that enables them to *experience* the game (e.g., Kolb 1984; Mendler de Suarez et al. 2012; Asplund et al. 2019), we focus on a small region with a specific geographical setting and infrastructure exposed to climate hazards. The Inverclyde area on the Firth of Clyde and western extent of
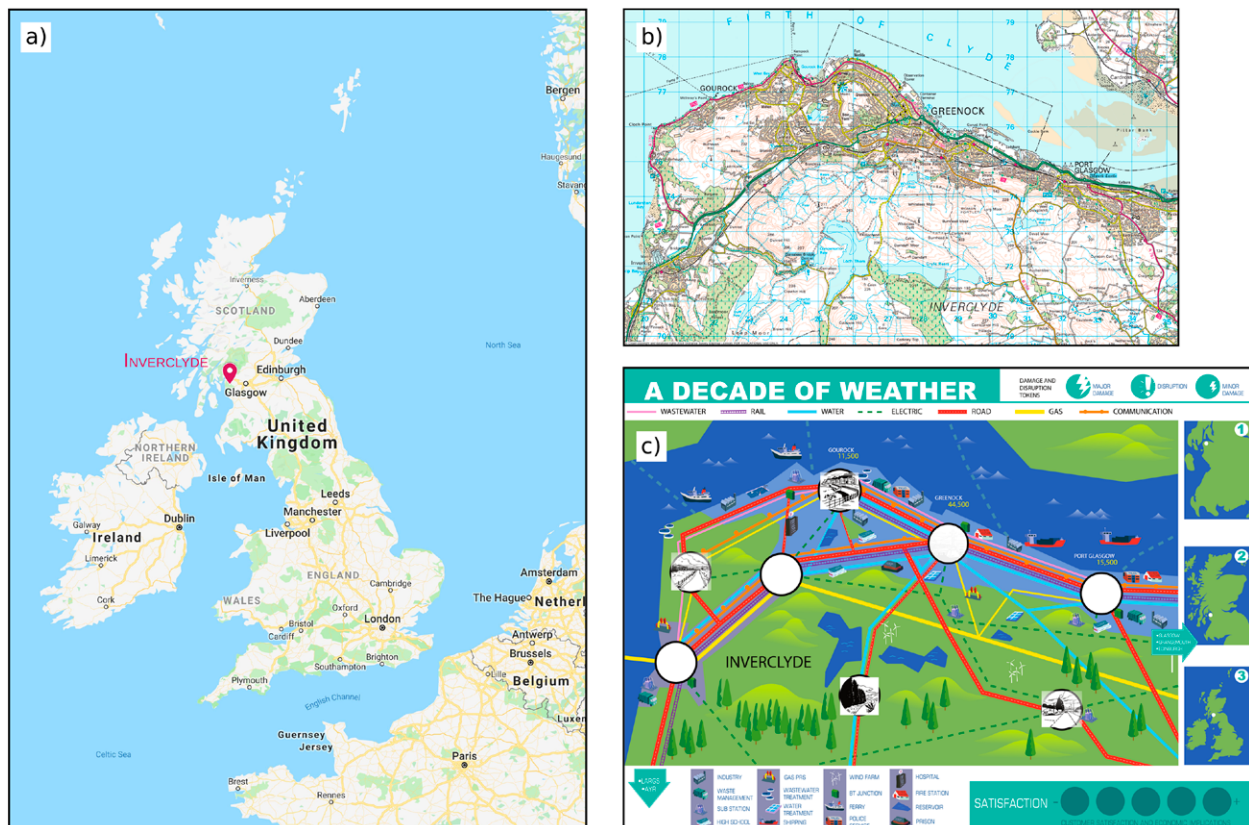
Fig. 1. From the map to the game board. Shown are (a) a map showing the geographical location of the Inverclyde area near Glasgow, Scotland, United Kingdom, Europe, used as the sample area for the study (map data copyright Google 2019), as well as (b) a geographical map of the Inverclyde area [Crown copyright and database rights 2018 Ordnance Survey (100025252)] and (c) a stylized version as main part of the game board with representations of the different infrastructure elements.

the Glasgow city region (Figs. 1a,b) was chosen by infrastructure operators during the scoping phase of the codesign process as a hotspot of multiple environmental risks to infrastructure with potentially significant socioeconomic implications ("Codesign process" section). These include damages from flooding (river, surface water, and coastal) with risks to properties, community facilities, utilities, and transport networks. Disruption of road and rail is amplified by a lack of diversion routes due to local topography (the narrow corridor between hills and the sea). Local disruption also has implications for regional infrastructure provision that connects through the area.

The paper is structured as follows: the development of the game is described, focusing on the codesign and extraction of the decade of weather, before a summary of final game rules, remarks on the game characteristics, and a report on the game-playing workshop. Lessons learned are structured around the aims of the project, covering the communication of projections and hazards, exploring climate impacts in the Inverclyde area, the game approach as a tool for stakeholder engagement, and suggestions for further development of the game. Conclusions complete the paper.

Developing the game

Codesign process. Key stakeholders were involved from the inception of the project, ensuring its salience and relevance. Table 1 summarizes the project's five phases of codesign and stakeholder engagement, and Table 2 stakeholder participation.

At the proposal writing stage infrastructure operators (Table 1) were asked if they would be interested to codesign and test a game. They did, seeing the approach as novel and engaging. The Inverclyde area was identified as a case study for testing whether a serious game could help identify vulnerabilities and inform adaptation.

After funding was secured, the stakeholders were invited to a scoping meeting to develop the research design. The 2050s was identified as the preferred decade due to its relevance to infrastructure capital investment programs, as well as significant projected climate change. Potential additional infrastructure operators were identified, as well as the most suitable local managers to be invited to play the game. To simplify the game and focus on the most important infrastructure it was agreed to not use realistic maps (like the Ordinance Survey map in Fig. 1b), but instead to produce a stylized game board (Fig. 1c). This also avoided security concerns around the exact location of critical infrastructure. The choice of climate hazards and their possible definitions were discussed to ensure consistency with those used by stakeholders, for example, based on the National Risk Assessment and Flood Risk Management.

In the next stage of the project, bilateral interviews with selected stakeholders informed the definitions chosen for the hazard events.

The main game design tasks consisted of deciding how to represent local infrastructure and of determining the game mechanics.

Each infrastructure operator completed a questionnaire (appendix A) to gather information on key infrastructure in the area and connection to wider networks. The questionnaire also asked them to identify interdependencies with other types of infrastructure using a matrix-based approach for both provision of services under normal operations and response and recovery following a disruptive event [based on a tool developed by the Infrastructure Operators Adaptation Forum (IOAF); IOAF 2017]. The responses formed the basis for discussion between operators at a game design and trial workshop.

A visual communication company (Scriberia Ltd.; www.scriberia.co.uk/) was contracted to work with the project team to design the game and its components. The preliminary game mechanics were tested with infrastructure partners at the game design and trial workshop. Stylized visualizations were iteratively adjusted according to the stakeholder feedback, including a game board approved by the infrastructure operators (Fig. 1c). The project team

meanwhile further developed the game mechanics, which continued to be discussed with stakeholders and play-tested by the project team.

A range of future socioeconomic scenarios were also developed that would allow for a discussion of changes other than climate hazards, which are not included in the main game. Which scenarios to consider based on assumed impacts on the infrastructure was briefly discussed at the game design and trial workshop. The project team then compiled a more extensive list of possible scenarios, which the stakeholders were asked to rank by interest using

Table 1. Development of the game in codesign with infrastructure adaptation stakeholders. For each phase, the date, main motivation, means, and outcomes of the interactions are listed.

Phase	When	Why	How	Outcomes
Scope	May 2017	**Proposal development**—National infrastructure providers were asked for interest in serious game and for a suitable region to pilot the approach.	Bilateral e-mail and phone communication	• Stakeholder commitment secured
				• Inverclyde identified as pilot region
	Nov 2017	**Scoping workshop**—The project plan was reviewed to check whether stakeholders remained interested and to plan activities. Risk categories to address in the game were discussed.	2.5 h meeting	• Commitment and suitability of the Inverclyde confirmed
				• 2050s decade agreed on
				• Stylized approach for the game agreed on
				• Codesign process agreed on
				• Main types of hazard events agreed on, need for bilateral follow-up to agree on hazard definitions identified
				• General approach to game development agreed on
Information gathering	Dec 2017–Feb 2018	**Interviews**—Hazard thresholds relevant to individual sectors and possible implementations of different types of flooding were discussed in bilateral communication between the project team and selected stakeholders.	Bilateral phone interviews and meetings	• Heatwave definition decided
				• Use of return periods and flood maps agreed on
	Jan 2018	**Infrastructure questionnaire**—Stakeholders returned preliminary information on main infrastructure elements in the case study area as well as known infrastructure vulnerabilities and interdependencies.	E-mail communication	• Infrastructure information per stakeholder prepared
				• Data confidentiality issues identified
Design and trial	Feb 2018	**Game design and trial workshop**—Stakeholders discussed their interdependencies to climate hazard before trialing three rounds of the game based on preliminary game mechanics suggested by the project team and an initial design of game board and materials. The game mechanics and visual design were afterward reviewed. Future socioeconomic scenarios were briefly discussed.	6 h workshop	• Interdependency discussions raised interest and expectation for the game
				• Main infrastructure per stakeholder identified and game board representation agreed on
				• The game's general flow worked well, but some aspects were confusing; detail in damage assignment reduced, interval rounds introduced, and shared satisfaction assessment suggested
				• Several ideas for refining the game materials including clearer board design, more meaningful tokens, and simpler characterization of events' magnitude/extremeness suggested
Play	Apr 2018	**Gaming workshop**—12 stakeholders played the game.	4 h workshop	• The game was played successfully and led to lively discussions among participants
Evaluation	May 2018	**Follow-up questionnaire**	E-mail communication	• Lessons learned on the strengths and weaknesses of the game approach
				• Suggestions for future improvements

Table 2. Stakeholder participation in the codesign. For each stage, the number of participants per stakeholder is given.

Phase	Scope		Information gathering		Design and trial	Play	Evaluation
	Proposal development	Scoping workshop	Interviews	Infrastructure questionnaire	Game design and trial workshop	Gaming workshop	Follow-up questionnaire
	May 2017	Nov 2017	Dec 2017–Feb 2018	Jan 2018	Feb 2018	Apr 2018	Apr 2018
Transport Scotland—The Scottish national transport agency	1	2	1	1	1	2	2
Scottish Water—The national water utility company	1	1	1	1	1	3	2
SEPA—Environmental regulator and responsible for flood forecasting and warning as well as strategic flood risk management	1	2	3	—	1	1	1
SGN—Gas distribution company in Scotland and southern England	1	2	—	1	2	4	3
SP Energy Networks—An electricity supply network company	0	0	—	1	0	0	0
Inverclyde Council—The local authority	1	0	—	1	1	1	1
Climate Ready Clyde—Regional climate impact adaptation advice and support initiative	1	1	—	—	2	1	1

on online poll. The project team developed the top four further and created corresponding scenario cards along with graphics.

The process of codesigning the game with infrastructure operators provided an opportunity for lively discussion about key infrastructure, potential interdependencies, and possible impacts from climate hazards.

Extracting a decade of weather. We extracted a decade of weather plausible for the 2050s from climate projections. While long-term trends in mean climate may also constitute a hazard, we focused on climate hazards associated with individual weather *events* (e.g., Seneviratne et al. 2012). Hazard events with a clear meteorological component (temperature, precipitation, wind) were considered, including heatwaves, cold spells, snow, storms, surface water flooding, river flooding, coastal flooding, and drought. The scope of the study did not include climate hazards with a complex and poorly understood link to specific weather, like slope instability and wildfires, but players might nonetheless discuss them during the game.

We use the regional climate model (RCM) projections from the U.K. Climate Projections 2009 (UKCP09; Murphy et al. 2009) by the Hadley Centre for Climate Prediction and Research (2008). These are driven by the A1B emission scenario for greenhouse gases and other climate forcings (Nakićenović and Swart 2000). The newer UKCP18 projections, derived from a different climate model and driven by different emission scenarios, show larger changes compared

to UKCP09 in terms of temperature and precipitation, that is, even hotter and drier summers and warmer and wetter winters (Lowe et al. 2019). The hazard profiles of the weather events considered here will therefore differ in UKCP18 from the ones in UKCP09, with some types of events being more likely/severe and others less so; high-temperature extremes in Scotland, for example, are projected to increase more in UKCP18 (Undorf et al. 2020). As we did not assess quantitative changes in hazard profiles, our findings are equally relevant for these newer projections and in case anthropogenic emissions follow different trajectories, including those consistent with the Paris goals of limiting warming to less than 2°C (UNFCCC 2015; IPCC 2018).

The data were processed as follows. As baseline period we used 1950–2000. For temperature, we corrected the projections for each grid point in the model domain with respect to their bias in mean and variance of the daily distributions during that period compared to E-OBS observations (Haylock et al. 2008) using the "underlying bias correction" as in Holmes et al. (2017). High or low temperature events in the Inverclyde area and all U.K. administrative regions were then identified from the fraction of grid points where absolute thresholds are crossed based on definitions from Public Health England et al. (2015, 2018). For regions in Scotland, we adopted the thresholds for northeast England as the climatologically closest region.

Hazard events relating to precipitation, sea level pressure, or wind speed were identified from exceedance of percentile thresholds derived from the baseline period, and characteristics of associated flood hazards derived from flood extent maps (Scottish Environmental Protection Agency 2018) for the respective return period. We identified coastal flooding from extreme depression over one of the sea areas relevant for past storm surges in the area (Sabatino et al. 2016). Drought refers to a precipitation deficit at time scales relevant for reservoirs. For a more detailed description of the methodology see Undorf et al. (2019, hereafter UTHMW19).

Compared to studies with a purely meteorological–scientific focus on one type of hazard (IPCC 2012), the analysis is relatively simple and aims to be easily replicated for other locations. The translation from climate model output to infrastructure hazard required assumptions on elements not included in the model, for example tide height in the case of coastal flooding. The extracted sequence of events is a physically plausible realization of future weather. In particular, this includes the consistent treatment of dependent hazards (e.g., river and surface water flooding). We primarily identified each type of hazard event separately, although concurrent events with moderate individual magnitude/return times were also considered. For example, most river flooding events were accompanied by surface water flooding and many by storm indicators (high wind speed and/or low pressure), while all heatwaves were followed in the same year by some degree of drought. This treatment avoids the potential underestimation of risks in compound events (Zscheischler et al. 2018).

We extracted events for each of the RCM's 11 perturbed physics ensemble (PPE) members, differences between which represent uncertainty due to physical processes and internal climate variability. We then chose from the ensemble member afixk, which we judged to be most interesting for the game purpose in terms of event type variety and order as well as potential impact—other members had for instance only flooding and storm events or were dominated by heatwaves. Each event was described in terms of its meteorological characteristics and the likelihood of occurrence in the baseline climate as a measure of its "extremeness." For coastal flooding, we gave the return period of the sea level depression, set this into relation to the highest storm surge on record, assumed a coinciding spring tide, and highlighted additional projected sea level rise.

To capture potential effects on the Inverclyde area from events elsewhere in the United Kingdom, some events in other regions were included. We also described the weather in the interval between events. For each event and interval, we created a game card that contained a graphical illustration along with the climatological information (Fig. 2). For a description of the full event sequence, see appendix B, and for all event cards including the graphics,

UTHMW19. We stressed to all involved that this was a plausible realization of future climate, but that there was considerable uncertainty in projections of the 2050s climate.

The game

Rules of the game. In *Cascade*, players provide present-day infrastructure services as they experience a plausible decade of 2050s weather. They are grouped around the game board, which is a stylized map of the Inverclyde area representing geography, key elements for each infrastructure type, and public services as they are today (Fig. 1c). Represented on the board are communications, electricity, gas, railways, roads, wastewater, and water. Each player is responsible for one infrastructure type or local authority services and has tokens that represent disruption or damage.

The decade is divided into game rounds based on the occurrence of hazard events (appendix B), so that individual rounds cover time periods of varying lengths. There are nine event rounds, each followed by an interval round. In an event round, the hazard event is presented to the players, who discuss its impacts and assign any resulting disruption and/or damage to their infrastructure by placing tokens on the board. Players then assign secondary disruption and/or damage that results from dependencies from other infrastructure. They then discuss hypothetical customer satisfaction and economic implications of the disruptions, and take notes in a template note-book provided (see UTHMW19). In an interval round, the players discuss potential recovery of their services/infrastructure and remove disruption and/or damage tokens from the board. They are asked to use their judgement to consider what resources might be available for recovery and the implications of impacts outside the Inverclyde area, as well as local infrastructure interdependencies. Again, they discuss customer satisfaction and take notes. After playing the decade of weather, the
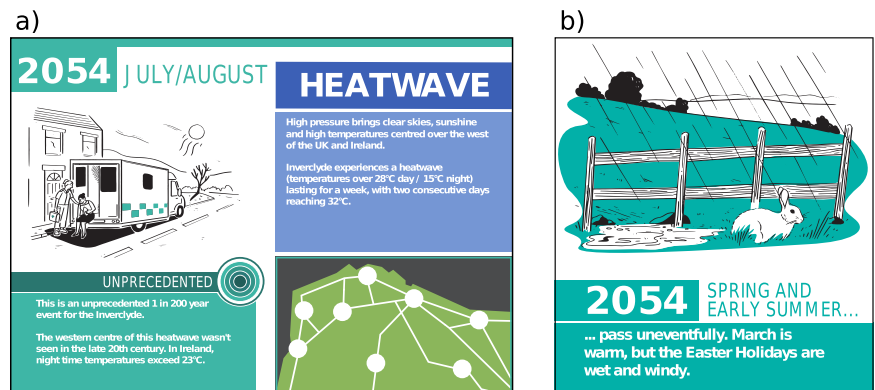

Fig. 2. Example game cards for (a) an event round, in which a hazard event is described that might damage and/or disrupt infrastructure services in the Inverclyde area, and (b) an interval round, in which the time period before the next hazard event is described that might allow for some recovery of damaged and/or disrupted infrastructure elements/services.

participants are asked to discuss what might have been different under future socioeconomic scenarios. For a full description of the game rules see UTHMW19.

Game characteristics. As a serious game, *Cascade*'s design reflects its purpose, including the intention to identify potential interdependencies and vulnerability hot spots not previously known to the project team or players. The resulting game has the character of a discussion tool, with limited choices made by the players and not much of a feedback system (e.g., McGonigal 2011), but still with clear traits of a board game.

The different components determining climate risks (IPCC 2012; Aitsi-Selmi et al. 2015) are distributed across game elements: assets are represented on the game board, their vulnerability (and more specific exposure) is subject to the players' knowledge, and the hazard is specified on the game cards.

Some projected global climate change is described on the game cards to set the regional weather in context. Many of the regional hazard profiles are projected to change in the coming decades (Mora et al. 2018; Murphy et al. 2018; IPCC 2012, 2013, 2018), so that the climate

hazards to infrastructure might not be unique to the future, but have greater (flooding, heatwaves) or smaller (cold spells, snow events) magnitudes/likelihoods than presently. Therefore, playing the game can communicate climate hazards and identify infrastructure vulnerabilities also with regard to present rather than future climate, as might result either from design shortcomings or the impacts of recent climate change on hazard profiles (e.g., Kendon et al. 2019; Stott et al. 2016; Otto et al. 2018; Undorf et al. 2020).

Playing the game. The game was played in a Glasgow venue easily accessible to all stakeholders. The 4 h workshop started at 1100 LT and was attended by 12 people representing the stakeholder groups who had been involved in the codesign (Table 2), including 6 participants who had not been previously involved in the project. The group was well mixed in terms of professional experience, age, and gender; for the workshop facilitation plan see UTHMW19.

Following a brief introduction to the project, the rules of *Cascade* were explained by the workshop facilitator, who also guided the players through the game rounds and facilitated discussion. The moderation ensured that the discussion included all players, with the facilitator explicitly asking individual players for their opinion, summarizing key points while ensuring correct interpretation, and reminding players to keep the discussion focused or to move on to stay on schedule. Another project team member acted as the "weather presenter," describing the hazard and interval events throughout the game. Two other project team members observed proceedings and took notes, and the discussion was recorded.

The stakeholders were curious on arrival and actively engaged throughout the game (Fig. 3). The first few rounds took approximately 30 min to play, but as players became familiar with the game mechanics, rounds took around 10 min each. We were unable to play the last few rounds due to time constraints, but the major hazard events of the decade were played in full. There was lively discussion throughout focusing on detailed impacts and interdependencies for each infrastructure. For example, disruptions to water supply affect trains because toilets cannot be flushed, and the resulting stench is a major cause of customer dissatisfaction. A summary of impacts in the Inverclyde area is discussed in the "Exploring impacts in the Inverclyde region" section.

To stimulate discussion and reflection on how wider socioeconomic changes by the 2050s might have impacted on their response to the game, players were presented with four short scenarios: 1) *an electric future*, 2) *growing population pressure*, 3) *lagging infrastructure investment*, and 4) *technological breakthroughs* (available in UTHMW19). Due to time constraints they considered two of them (1 and 3; results in the "Exploring impacts in the Inverclyde region" section). The session then concluded.

Lessons learned

The project team compiled lessons learned during the game based on notes taken while observing the playing of the game, transcribed audio recordings of the session, players' notes recorded in template notebooks, and photographs taken after each round. To capture postgame reflection we asked players to complete a simple follow-up questionnaire, which was sent two weeks after the game session. Ten out of 12 participants responded. We include nonattributed quotes (in italics) to protect anonymity, with full responses from the questionnaire in appendix C. This section is structured around the aims of the project.

Communication of projections and hazards. The game took a novel approach that used an extracted decade of weather from climate projections to create a sequence of events ("Extracting a decade of weather" section) for use as game rounds. It was clear that the players were able to immediately relate to the "weather events" as they were presented, in a weather forecast style, during the game. The comparison of how often a similar event occurred in the past—from "frequent" to

Fig. 3. Photographs illustrating the game-playing workshop. (from top left to bottom right) The game setup, the introduction to the game, the phase in which the players explain their infrastructure, a hazard event presentation, the phase in which the players discuss and assign damage and disruption, the game board in a state with damaged and disruption present.

"unprecedented"—worked well as a way of quickly conveying change. Although some players were familiar with UKCP09 probabilistic projections for 2050s, using a series of weather events lead one participant to comment that it provided "*A greater insight into the type of weather scenarios that could occur from climate change and the effects on infrastructure, quality of life, etc.*" Although another felt that "*some of the weather events were confusing in nature... e.g. sunny weather event.*"

The game mechanism required players to use their expertise to relate the hazard of weather events to impacts on their infrastructure. This design has the advantage of minimizing time-consuming data collection and analysis to develop the game and avoiding security issues. Overall players were able to identify a wide range of relevant potential impacts to drive the game and discussions. We did observe that many players had difficulty interpreting the

hazards, with uncertainty over issues like the spatial extent of flooding. A participant observed that in a future version "*the scenarios would need to be tightened up and more specific to ... see the knock on effect.*" Providing more specific information could benefit participant understanding, but would need to be carefully balanced with simplicity.

Exploring impacts in the Inverclyde region. The players were able to identify a wide range of impacts on infrastructure associated with weather events in the game. For many impacts they offered specific examples of past incidents either from the region or in other parts of their networks. We observed that for unprecedented events—like a catastrophic storm surge—they were aware that it was a risk, but appeared less sure of the spatial extent of impacts. As the game relied on players to identify impacts based on their knowledge and the game situation, we expect that some impacts were missed and others overstated. One participant commented that "*At times I felt that we were having to create additional problems to ensure there was a knock on effect.*"

The game revealed a wide range of interdependencies between operators, some of which players were aware of, but others they had not previously considered. Participants had a good understanding of the impacts of other infrastructure failures on their infrastructure, but much less so of the failure of their infrastructure on others. Examples identified by the stakeholders while playing *Cascade* include:

- Access routes to repair gas, electricity, and water assets are often minor roads that are not identified as priority routes. These are typically managed by the local authority, whereas Transport Scotland manages the trunk roads.
- All infrastructure operators relied heavily on the electricity network to run operations.
- Telecommunication infrastructure (especially cellular networks) is critical to support repair activities on sites.
- Soil shrinkage due to drought can lead to damage of underground infrastructure, where burst water pipes can cause damage to the gas network.
- Major disruptions elsewhere in the United Kingdom can impact the availability of skilled repair teams in the Inverclyde.

Although playing the game identified a number of potential interdependencies and cascading impacts, we observed that the exploration of these was fairly superficial. This was expected from the game design, as the turns were kept short (to move through multiple events) and we did not provide specific information. We also observed that players had different levels of local knowledge, which made it difficult for some of them to talk in detail. A focus on (a) more specific hazard scenario(s) might explore these in more detail, but would become unwieldy in the overall game structure.

The game included recovery phases. When playing, participants felt that damage could be quickly repaired; even for the most extreme weather this only took a matter of weeks. These included (i) a combined surface water and river flooding event, with river flooding a third more severe than seen in the historical period; (ii) a combined coastal and river flooding event a month later with unprecedented levels of coastal flooding due to additional spring tide and projected sea level rise; and (iii) a heatwave with a 1 in 200 year return period compared to the 1950–2000 baseline period. This lead participants to suggest that "*most organisations who were involved seemed to be in a pretty good place to deal with extreme weather events*" and that "*our infrastructure systems are relatively robust, with possibly some organisations more likely to be affected than others.*" There may be overconfidence in these statements, with judgement on the extent of repairs based on their expertise and past experience. This would be more likely if impacts were far beyond experience, but this was not the case in the game played—although we do note that rounds in play testing were far more destructive, so

player response may differ depending on the game situation, the mix of expertise, and group dynamic. Impact of coastal flooding on defense structures that diminish the present risk of coastal erosion (Fitton et al. 2018) might have been missed due to a lack of specific knowledge by the group of players.

The game was played assuming present-day infrastructure and society responding to a 2050s climate. In the scenario-based discussion at the end of the session participants suggested that a future infrastructure system and society would be affected differently. For example, there might be a huge increase in overall risk of failure with a future society heavily reliant on electricity. When flooding occurs, an impact on power supply (including outages) could depend on local storage capacity—with other operators needing powered backup generators for water pumps and staff using an electric vehicle fleet. However, the participants also highlighted that experience of hazard events between now and the 2050s might result in an increase in adaptation capacity. There might also be socioeconomic changes like those in demographics (e.g., due to migration and health improvements) both in the study area and elsewhere. Several participants emphasized that uncertainty regarding future policy is already, and will likely continue to, inhibit them from implementing innovation in their infrastructure, resulting in reduced mitigation as well as adaptation.

Taking a game approach. This pilot study demonstrated that the game approach we took encouraged fruitful discussions among infrastructure operators—enabling them to share knowledge in an informal, playful situation. This is supported by participants' very positive response in the follow-up questionnaire (appendix C). It was seen as "*novel when compared to a conventional workshop*" and "*helped to make the scenario more 'real' and less theoretical,*" and "*visually put the scenarios in context.*" They also reflected that "*understanding 'cascade' effects was very interesting*" and that "*the game was an excellent way to discuss interdependencies with other organisations.*"

Cascade relies upon player knowledge, so is highly dependent on the people participating. In our pilot we had a range of infrastructure operators, but were missing telecommunications and electricity on the day. The amount of local knowledge also varied among players and the infrastructure operators, which may have limited discussions on interdependencies and cascading impacts. One participant suggested that the game should be played "*with a more diverse set of participants, including bringing in more local knowledge from planners, emergency response services, politicians, the public, and local property owners.*" There would be a clear benefit to more people with local knowledge playing, although there are practical limits to the number that can play a single game—playing multiple games would allow for an informative comparison.

Having played the game, several participants suggested there was a need for further knowledge sharing and collective discussions on the strategic context of climate change adaptation. There were also various calls for follow-up activities to "*understand adaptation options that need to be developed to minimize the consequences highlighted.*" The pilot study was not set within a wider program of planned activity by the infrastructure operators in the Inverclyde—although they do interact there and on a regional basis through initiatives like Climate Ready Clyde. Using the game approach as a tool in a wider program would significantly increase its benefit.

Participants were generally "*impressed with the game in its current format.*" There were minor suggestions to modify the design, including making utility lines easier to see and adding a timeline at the bottom of the event cards to show progress into the decade (starting in 2050). Trade-offs around the level of detail to include were acknowledged—suggesting it worked well for discussion, but was too coarse to understand the implications of specific flood events. At times discussions were challenging to facilitate, requiring prompts at the start of the game

and interventions to focus when the game was in full swing. Once the players understood the mechanics of the game, rules were sometimes ignored, for example, jumping directly to secondary impacts from other infrastructure instead of focusing only on direct impacts on their own infrastructure. It would be challenging to facilitate the game with more than 12 participants.

Future development. All respondents to the follow-up questionnaire had suggestions for future development of the game (see appendix C for full details) including replication of the game in other regions, inviting different stakeholder groups and focusing on different age groups and the public, converting it to a computer-based game, expanding the diversity of scenarios, and including additional types of both climate and nonclimate hazards. There were also suggestions to adapt the game to "*a 'kit' so organisations could customise a board for use in their own area.*" Specific organizations that could be interested in future use of the game were identified including the Scottish Government Resilience Division, local authorities, Sustainable Scotland Network, and Community Planning Partnerships.

We agree there is potential to deploy *Cascade* with wider groups of stakeholders, above all those providing telecommunications, electricity, and health services, as well as in other locations and at different spatial scales. It would be good to bring in additional expertise to explicitly include hazards like wildfires that were omitted due to complex links to future weather. Some other potential developments include the following:

- Additional analysis of observed climate data alongside records of local impacts could lead to better comparability between projected and historical events, and aide in communicating the magnitude of projected events.
- The hazard events could include more information on the potential scope of impacts, for example, on flood extents—although this would need to be balanced with simplicity.
- The event extraction tools could be updated to access recently released UKCP18 data, which includes 28-member ensemble global projections (Lowe et al., 2019).
- The hazard events could be expanded to include those relevant to different locations and climates, with an updated set of illustrations, but careful consideration would have to be given to cultural contexts different from the United Kingdom that may affect the games suitability (e.g., Asplund et al. 2019).
- The "decade of weather" and the event cards could be used by themselves as an engagement tool for climate projections, something we have already trialed in a workshop with the Scottish Parliament.
- There is potential for a digital version of the game—or components of it—that could streamline play, or add more information. Although we do believe there is a benefit to face-to-face discussion and tactile interactions with a simple physical board game.

All game materials have been made available under a Creative Commons license as a basis for future development (UTHMW19).

Conclusions

The serious game *Cascade: A Decade of Weather* that we developed as an interdisciplinary project appears to be a useful tool for engaging stakeholders on climate adaptation. It allowed communication of climate hazard (change) and identification of potential interdependent risks by bringing together stakeholders with individual expertise and confronting them as a group with a sequence of climate hazards in an experiential learning setting. Using climate model projections as input ensured that the climate hazards are physically plausible. While the game focused on infrastructure, the stakeholder discussions were not restricted to this sector, but included other adaptation areas too (e.g., human health and wellbeing, agriculture).

With the caveat that neither long-term trends in mean climate nor political or social impacts of climate change elsewhere were considered, and wildfires and coastal erosion not explicitly included, the participating U.K. infrastructure providers felt that they could presently cope with 2050s climate change, and none of the projected hazard events were anticipated to cause catastrophic impact cascades on infrastructure. Whether these expert judgements are realistic or overoptimistic could be analyzed in a follow-up study.

Appendix A: Infrastructure questionnaire

The following questionnaire was given to infrastructure stakeholders to gather information on infrastructure in the Inverclyde region and to capture thoughts on interdependencies prior to the game (cp. Table 2).

Purpose. We are trying to capture basic information on each of the infrastructure sectors/operators. This will provide background information for the development of the GAME—most importantly it will be information we can share between ALL PROJECT PARTNERS at a workshop to develop the stylised "game board," which is planned for early 2018.

Note: we aren't seeking detailed information—and if something isn't available, that is fine. This questionnaire has four sections: two on page that ask you to consider your infrastructure and two further tabs/worksheets to look at interdependencies based on IOAF Matrix Tool.

1. What are the key elements of your infrastructure in the Inverclyde area?
   Consider: Where is it located? How it is connected? Is there a hierarchy (major, intermediate, local)? Are there any "hot spots" for vulnerability?
   if possible, also simple map(s) would be useful
2. How is your infrastructure in the Inverclyde connected to wider networks?
   Consider: What are the important regional, national, and international connections? What infrastructure outwith Inverclyde is critical for delivering your infrastructure services? Would a simultaneous impact elsewhere impact on your operations or response in the Inverclyde?

How to use the following tables…You need to fill in how {row} your infrastructure depends on other infrastructure and {column} other infrastructure depends on your infrastructure. Some IOAF members found it difficult to fill in the table without sub-categories (e.g., infrastructure or service type); this is optional in our table. You may also consider internal dependencies within your sector.
The score options in the drop-down menus are

1. High
2. Medium
3. Low
4. Not significant

Interdependencies: Provision of services. Please identify how **normal operation** of {row} your infrastructure depends on other infrastructure and {column} other infrastructure depends on your infrastructure. For each also select a "perceived" score on the importance of the overall dependency (use pull-down list). The focus is on the Inverclyde, although dependencies may arise elsewhere.

A copy of Table A1 was provided with drop-down menus as described above.

Interdependency: Response and recovery. Please give details on how **following a disruptive event the response and recovery** of {row} your infrastructure depends on other infrastructure and {column} other infrastructure depends on your infrastructure. For each also select a "perceived" score on the importance of the overall dependency (use pull-down list). The focus is on the Inverclyde, although dependencies may arise elsewhere.

Another copy of Table A1 was provided with drop-down menus as described above.

Table A1. Matrix part of the infrastructure questionnaire, used to capture stakeholders' thoughts on interdependencies prior to playing the game.

		Gas	Electricity	Transport	Telephony/ICT	Water	Inverclyde Council
Gas	Subcategories (if needed)		Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>
			• • •	• • •	• • •	• • •	• • •
Electricity	Subcategories (if needed)	Score: <select here>		Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>
		• • •		• • •	• • •	• • •	• • •
Transport	Subcategories (if needed)	Score: <select here>	Score: <select here>		Score: <select here>	Score: <select here>	Score: <select here>
		• • •	• • •		• • •	• • •	• • •
Telephony /ICT	Subcategories (if needed)	Score: <select here>	Score: <select here>	Score: <select here>		Score: <select here>	Score: <select here>
		• • •	• • •	• • •		• • •	• • •
Water	Subcategories (if needed)	Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>		Score: <select here>
		• • •	• • •	• • •	• • •		• • •
Inverclyde Council	Subcategories (if needed)	Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>	Score: <select here>	
		• • •	• • •	• • •	• • •	• • •	

Appendix B: A Decade of Weather—The event sequence

The sequence of climate hazard events used as game rounds (A1–9: event rounds; B1–9: interval rounds), extracted from the UKCP09 climate projections as described in the "Extracting a decade of weather" section, and in more detail in UTHMW19, is summarized as follows. The first year of the decade, 2050, is uneventful, with temperatures and rainfall similar to the simulated average of the 2050s. A dry winter 2050/51 as well as a hot spring and summer 2051 precede a (A1) drought in September 2051 over most of the United Kingdom, which might be similar to the driest period in the baseline climate 1950–2000. After a (B1) cool and rainy month later, a storm in November 2051 brings (A2) surface water flooding, and river flooding of unprecedented levels, to the Inverclyde. After only (B2) two weeks, this is followed by (A3) record-level storm-induced coastal flooding, again combined with river flooding, during Christmas 2051. After an uneventful (B3) January 2051, a storm causes (A4) coastal flooding over northeast Scotland and high winds over other parts of the United Kingdom excluding Inverclyde in February. Now (B4) two years pass without extreme events in the Inverclyde. In January 2054, the area sees a similar (A5) compound flooding event to that in late 2051 while temperatures are below zero, but this time this is assumed to coincide with a lower tide so Scotland and northern England experience less serious coastal flooding. After (B5) two calm weeks, a (A6) cold spell with snow affects Inverclyde and the rest of the United Kingdom in February 2054, which, although not unusual in 1950–2000, is rare in the 2050s. (B6) Spring and early summer 2054 are uneventful, until a (A7) heatwave happens in the summer, with temperatures in the Inverclyde reaching 32°C on two consecutive days. These temperatures are a 1 in 200-year event given the baseline climate, and the heatwave is centered over Ireland, which is unknown from the past. (B7) More than four years pass with only minor flooding events in Inverclyde every couple of months and more significant storms; (A8) southern England, meanwhile, experiences an unprecedented river flooding event in December 2055. After (B8) three years of more small-scale surface or river flooding in the Inverclyde and winter storms, the decade ends with a (A9) surface and river flooding event in Inverclyde in winter 2058/59 and (B9) a quieter rest of the year 2059.

Appendix C: Stakeholder feedback

Responses to follow-up questions sent two weeks after the workshop by e-mail to all 12 workshop participants. Responses were received from 10 participants who have been randomly numbered to ensure anonymity.

a. Thinking back to the workshop, what are the main things you have learned during the game and the following discussions?

Participant 1—"One of the main things that I learned was the impact that each organisation can have on one another, it wasn't something that I was overly aware of as my focus was always centred around Scottish Water. From now on I will be looking at other organisations to see what impact I could inadvertently causing."

Participant 2—"It was very interesting to learn some specifics, such as how a water mains burst can impact the gas network. Understanding 'cascade' effects was very interesting."

Participant 3—"The game was an excellent way to discuss interdependencies with other organisations. I made some initial assumptions that had to change after discussions listening into the impact of the weather event on area. I had to leave early and this may have been discussed but I also would have liked to have discussed how the scenario would have run with different levels of preparedness (and this in built resilience)."

Participant 4—"What I learned following completion of the levels I took part in, is that most of the organisations who were involved seemed to be in a pretty good place to deal with extreme weather events and it would probably take a catastrophic event of biblical proportions to severely disrupt all of the organisations."

Participant 5—"A greater insight into the type of weather scenarios that could occur from climate change and the effects on infrastructure, quality of life, etc."

Participant 6—"The difficulty in describing weather conditions in a manner which results in everyone applying a consistent interpretation. That our infrastructure systems are relatively robust, with possibly certain organizations more likely to be affected than others—i.e. Scottish Water, which when you think about it makes sense. Also, I do think there are potential interactions that are not always obvious."

Participant 7—"Learnt how interrelated the various services are and how important it is to work together. The question becomes how do we adapt to the shared knowledge we have mitigate or better prepare for some of the scenarios highlighted in the game."

Participant 8—"The interdependences between the different infrastructures, not all are obvious. E.g. we rely heavily on transport, particularly roads and ferry to access our operational sites. The routes we may require access to are not likely to be priorities for Transport for Scotland who are focusing on the main roads."

Participant 9—"That most operators had a good understanding of impacts of an infrastructure failure of others on THEIR network, but not vice versa, and that many had not yet begun those collective discussions, at least in a strategic context for adaptation."

Participant 10—"Impacts of water in the gas network."

b. What should be the next steps following the workshop?

Participant 1—"For me I think a detailed report on what actually happened throughout the game would be the next step and possibly a discussion on the detail."

Participant 2—"Next steps: potentially a 'kit' so organisations could customise a board for use in their own area? (Have I leapt too far ahead here?!)"

Participant 3—"A group discussion on how to develop the game further. See my suggestions for this in 4. below. I also think that a discussion with NERC would be useful as I am working on another similar project with the Anglia Ruskin University and other utilities on a computer modelled network interdependencies—a comparison of both would be valuable. I would also be interested in hearing about the benefits of the game approach to other participants."

Participant 4—"I feel a wash-up session to discuss the feedback from everyone involved with the game would be a good next step, I also feel that this could be a good event to tighten up the game formation and level scenarios."

Participant 5—"Promote the results of the game test to the public sector, utilities and transport providers, etc. with a view to them using the game to interact and consider the

effects of climate change and what should be done to adapt. This could be done via the Sustainable Scotland Network, Scottish Energy Officers Networks, Community Planning Partnerships, etc."

Participant 6—"I would suggest that the concept of interacting constraints between different infrastructure types is relevant to a number of scenarios—not merely weather conditions, and on that basis it might be worth promoting through a local authority or Scottish Govt Resilience group."

Participant 7—"I would like to see a formal think tank develop from the workshop where all infrastructures come together and map how they can better make their services more resilient to changing climate scenarios."

Participant 8—"Further meetings to discuss actual detail around the interdependencies and actually come up with action plans if appropriate."

Participant 9—"We should bring together a wider range of partners to play the game—some were noticeably missing (e.g., telecoms), while others (e.g., Network Rail) would be able to bring more local knowledge. We should also consider its use at a more strategic scale (Glasgow City Region, Scotland?)."

Participant 10—"A follow up report would be useful—summarising learning for Inverclyde but also more generic points which could be drawn out in terms of learning—for each type of weather event."

c. Did you think the game format added value over a conventional workshop?

Participant 1—"It made discussion relevant and open ideally you would like representatives from other organizations."

Participant 2—"The game format did add value, I think it helped to make the scenario more 'real' and less theoretical/strategic. There was some 'flouting' of the game rules once people understood where they were heading with it—i.e. jumping directly to secondary impacts from other infrastructure instead of focusing only on direct impacts on their own infrastructure—but this shows how quickly the learning of interdependencies took place."

Participant 3—"Yes—particularly in the group discussions."

Participant 4—"I thought the idea of a game was novel when compared to a conventional workshop."

Participant 5—"Very much so as it encouraged greater interaction and discussion with regards the impacts of climate change through presenting a variety of scenarios. I found the game stimulating."

Participant 6—"Yes I still think it can, because it could be used to draw out hot spots of risk across infrastructure providers that might not otherwise be captured."

Participant 7—"Yes, helped to visually put the scenarios in context."

Participant 8—"Yes, it was more fun and easier to see the physical challenges rather than discussing it in principal. It also highlighted things I think would have been missed in a conventional meeting format."

Participant 9—"Yes—significantly. It enabled a more straightforward and interesting entry point for stakeholders into the issue of cascade and convergence failures, as well as the likely weather that organisations would be facing and the associated business implications. In addition, the emphasis on place helped engage some of the stakeholders."

Participant 10—"Yes, it was a good interactive approach."

d. Do you think it would be valuable to further develop the game?

Participant 1—"Yes"

Participant 2—"See 2"

Participant 3—"Yes—see 5. below."

Participant 4—"I am not entirely sure that it would be valuable to develop the game further in its current format, while it was an interesting concept, it was apparent that the likelihood of the weather events which took place during the game having a drastic knock on effect for each of the organisations would be unlikely. I felt that the majority of resilience measures which are currently in place, would most likely be able to cope with the event in the scenarios. At times I felt that we were having to create additional problems to ensure there was a knock on effect. I felt that if the discussion around a particular issue showed that the organisations could possibly deal with the event effectively, we speculated about knock on effects, rather than what was likely to happen."

Participant 5—"Yes, the game could be periodically refined based on new information concerning climate change, user comments, etc."

Participant 6—"I think it has potential but probably in a wider sense, looking to target and find those key 'hot spots.'"

Participant 7—"I think it would be interesting how other scenarios could be implemented into the game such as disaster relief and look specifically at other regions with varying levels of development. But I like the idea of focusing on a specific area, town or region."

Participant 8—"Yes but I feel it is nearly ready. Would be good to see how it works in other regions."

Participant 9—"Yes—in particular, with a view to steering stakeholder around to the discussions on adaptation options. While the discussion sparked by the game was valuable, the next step will be to understand the adaptation options that need to be developed to minimize the consequences highlighted."

Participant 10—"Not sure, it feels like a generic version of the game wouldn't be of much use, that it would have to be developed for specific areas. But that could be the challenge of further development—how to make it generic and still effective. Depends if the aim is to make

people think about the issues/impacts more generally or if it's to give them a better idea of the specific impacts in their own area/community."

e. If so, do you have any specific suggestions for improvements?

Participant 1—"I know this is a pilot however, looking at other areas maybe a benefit to all. I think the public that would be impacted could add value, even if someone acted the part possibly a stubborn customer and an open customer, to see if their opinions change throughout the game. Maybe a Scottish Government MP involved in the environmental change would benefit from the knowledge collated at such events."

Participant 2—"See 2!"

Participant 3—"Make it computer based to allow it to be run remotely at separate locations—also automate the icons, counters and the like to speed up the playing—could also consider developing different versions for different ages—this would allow different perspectives to be recorded and compared. This may also remove the requirement for a facilitator—although this can be beneficial especially given my comments about the benefits of group discussions. With reference to my answer at 1. a running of the game with different levels of resilience in systems may be useful. It could be useful to consider adding in some wild cards—these could be e.g. a cyber-attack or a worldwide pandemic! Finally I suggest a general tidying up of the board the various utility lines were difficult to see—this was based on Inverclyde but could be anywhere—as few additional interdependencies could also be included—e.g., a major refinery or a major distribution center."

Participant 4—"With the points I raised in question 4, I feel that the scenarios would need to be tightened up and more specific to make to ensure that we could see the knock on effect for organisations (e.g. severe storm causes power cut in area for 3 days etc), however I understand that we are trying to predict what could potentially happen with more extreme weather events due to climate change, therefore I am not sure how we could go tightening them up. I also like [...] idea of the game being a computer game and automated."

Participant 5—"No suggestions at present, was impressed with the game in its current format."

Participant 6—"If joint interest, trial on several other areas to seek out range of issues."

Participant 7—"Further development of the scope of the game to look at other potential climate related risk."

Participant 8—"Some of the weather events were confusing in nature... e.g. sunny weather event. The board itself makes sense. Not enough time to write answers in the logbooks which I guess holds some of the key info and learnings from each round."
Participant 9—No response.

Participant 10—"It felt like a wider range of people needed to be involved, especially from the local authority (for local knowledge) and perhaps emergency responders and representatives from property owners who could be impacted by the events. But also it would be useful perhaps for planners. However the problem is to keep the number participating manageable."

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