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Gamification for climate change engagement: review of corpus and future agenda

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Gamification for climate change engagement: review of corpus
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E-mail: daniel.fernandezgaleote@tuni.fi**Keywords:** climate change engagement, games, gamification, game-based learning, serious games, role-playing, research agendaSupplementary material for this article is available [online](#)

Abstract

Both bottom-up and top-down initiatives are essential for addressing climate change effectively. These include initiatives aiming to achieve widespread behavioral change towards reduction of greenhouse gas emissions as well as pursuing education regarding adaptation measures. While awareness of the issue of climate change is now pervasive, and actions are being taken at all levels of society, there is still much to do if international goals are to be met. Games and gamification offer one approach to foster both behavioral change and education. In this paper, we investigate the state-of-the-art of game-based climate change engagement through a systematic literature review of 64 research outputs comprising 56 different gamified approaches. Our analysis of the literature reveals a trend of promising findings in this nascent and growing area of research, suggesting the potential to impact multiple engagement dimensions simultaneously, as well as create an engaging gameful experience. Overall, the corpus appears to offer a fruitful balance in foci between climate science, mitigation, and adaptation, as well as a variety of formats in game-based approaches (i.e. digital, analog, and hybrid). However, shortcomings were also observed, such as geographic and demographic imbalances and the short duration of interventions. The reviewed studies yield a large number of results indicating climate change engagement through gamification, especially in the form of cognitive engagement, affect towards climate change-related topics, and in-game behavioral engagement with others. Nevertheless, heterogeneity in terms of contexts, designs, outcomes, and methods, as well as limited rigor in research designs and reporting, hinders drawing overall conclusions. Based on our review, we provide guidelines regarding contexts, interventions, results, and research quality and internal validity for advancing the space of game-based interventions for climate change engagement.

1. Introduction and background

Climate change is currently seen as the primary threat across the planet (Poushter and Huang 2019) for biodiversity and human societies. As scientists warn of the dire impacts from present global warming through, for example, rising temperatures, heavy precipitation events and droughts (IPCC 2018), hundreds of legislative bodies and governments have declared 'climate emergency' to signal

extraordinary resource mobilization (Climate Emergency Declaration 2020). At the same time such top-down governmental initiatives are implemented, widespread bottom-up engagement with and response to climate change is essential if targets for emissions reduction and energy saving are to be met (Hart and Feldman 2016).

To date, much progress has been made in understanding how to engage citizens and strengthen their motivations to reach equitable solutions (van

Valkengoed and Steg 2019). While past science communication has viewed climate change as a problem to be addressed by providing more information to the public (Moser and Dilling 2011), this information deficit model ignores other psychological barriers that stand between knowledge and concern and action, such as values, ideology, skepticism or distrust toward experts (Gifford 2011, Whitmarsh 2011).

Instead, experts have proposed to replace public understanding of science, which often adopts this approach, with public engagement in science, which focuses on dialog and acknowledges laypeople's situated understandings and contexts (Wibeck 2014). For example, appealing to societal and economic co-benefits of mitigation can have benefits in motivating those who deny anthropogenic climate change (Bain *et al* 2012). However, climate change engagement is not limited to understanding scientific facts or even the relevance of climate action. A person who is truly engaged with climate change is defined as manifesting three forms of connection: cognitive (knowing), affective (caring), and behavioral (acting) (Lorenzoni *et al* 2007), all of which can be connected to both mitigation and adaptation of climate change (Whitmarsh *et al* 2011).

Strategic engagement proposals have ranged from employing digital technology to provide 3D visualizations and interactive environments (Wibeck 2014) to an explicit mention of experiential learning environments (Stermann 2011). Experiential, inquiry-based, and constructivist interventions have been used in climate change education before (Monroe *et al* 2017). One opportunity is provided by gamification, understood as the use of games across society, culture and technology for purposes other than mere entertainment (Hamari 2019). Gameful designs continue to permeate our daily lives by supporting involvement in utilitarian contexts (e.g. education, health) through engagement and enjoyment (Koivisto and Hamari 2019).

This is not an entirely new concept: instrumental games exist since at least the middle ages (Von Hilgers 2012), while the tradition of digital serious games originates in the 1950s with the first digital computers (Djaouti *et al* 2011). However, games' increasing pervasiveness has led to several areas becoming gamified (Koivisto and Hamari 2019), especially where humans struggle with motivation and persistence such as education (Majuri *et al* 2018), health (Johnson *et al* 2016), and energy conservation (Johnson *et al* 2017). In the context of climate change, games and simulations have been used for almost forty years now (Robinson and Ausubel 1983). Diverse game reviews from the last decade show that the tendency has only grown since then (for example, see Reckien and Eisenack 2013) and evince that games address a wide range of learning goals, from knowledge increase to affective and behavioral engagement (Flood *et al* 2018, Rajanen and Rajanen 2019).

Four mechanisms in particular that have been proposed in prior literature (Den Haan and Van der Voort 2018, Dieleman and Huisingsh 2006, Flood *et al* 2018, Plass *et al* 2015, Schroth *et al* 2014, van Pelt *et al* 2015) as driving the effectiveness of games in generating outcomes other than entertainment are an increased motivation through engaging experience, learning through active experimentation, social interaction, and visual representation. First, gamification supports motivation (Koivisto and Hamari 2019) by providing experiences of flow and immersion (Hamari *et al* 2016), i.e. completely capturing the player's attention. Games often provide feelings of competence, autonomy, and relatedness (Rigby and Ryan 2011), which not only drive player engagement but can empower them to act. Thus, an engaging game experience can enhance players' cognition, create positive emotions, and motivate behavior that enhances the public's response to climate change, either within or out of the game's frame. Second, and according to Piaget's theories and cognitive constructivism overall, learning occurs when the information received from experience is assimilated and accommodated (Powell and Kalina 2009). Indeed, games often provide interactive spaces where reality can be experienced and transformed. As proposed by Kolb (2014), this would be the basis for knowledge creation. Later conceptualizations of his experiential learning theory seem to highlight four elements: a concrete experience situated in a physical and temporal context, critical reflection, context-specific abstraction, and active experimentation (Morris 2020). Games can support learning by affording hands-on experiences in real or simulated contexts, providing different levels of abstraction and focus on specific features of reality, and including moments for individual or group reflection. In addition, challenges in games can adapt to the circumstances of specific players, providing customized guidance and feedback, and allow them to fail with low consequence (Plass *et al* 2015). Especially when combined with other methods and spread across multiple sessions, serious games have been found to be more effective than traditional instruction (Wouters *et al* 2013). Third, games often facilitate social engagement, for example, in multiplayer games or through fictional characters. According to social constructivist theories, ideas are built through social interaction (Powell and Kalina 2009), an effective strategy in terms of climate change education (Monroe *et al* 2017). Working in groups has been identified as a relevant aspect in serious games' effectiveness (Wouters *et al* 2013). Even single player game experiences can satisfy relatedness needs through interaction with non-player characters (Rigby and Ryan 2011). This allows games not only to provide information, but also a safe space to collectively interact with its causes and impacts, and to effect action. Fourth, another important element of games, visual

representation, is believed to provide a series of learning aids and benefits to users, among which immersion, interaction, credibility, and self-assessment of climate change knowledge (O'Neill and Smith 2014), enhanced clarity, and understanding (Flood *et al* 2018). Furthermore, visuals improve the quality of deliberation and decision-making (Burch *et al* 2010).

Despite these promises, evidence on the effectiveness of game-based interventions to enhance climate change engagement is not well integrated. The literature, although offering many examples of specific game-based studies, does not offer an up-to-date synthesis of findings or a substantiated conclusion to guide research or practice. In particular, there is a lack of clarity on the contexts and target groups for which game-based solutions effectively enhance climate-related engagement, which design choices provide positive outcomes, to what extent individuals' engagement is actually improved, and how this improvement can best be measured and understood. These shortcomings in the literature are important because without a structured, evidence-based overview, game-based research for climate change engagement will remain in the domain of trial-and-error. In this context, an up-to-date systematic review of game-based climate change engagement research is needed to provide a broad picture of what scientists are attempting and reporting in this field, how, where and to whom, but also an explicit, informed direction regarding agenda-setting for the future.

This study is preceded by other reviews that examined similar research spaces. Some review articles have focused on a broader picture, for example by exploring social learning outcomes in game-based interventions about sustainability issues (Den Haan and Van der Voort 2018) or the use of simulations and serious games in sustainability education (Hallinger *et al* 2020). Others have investigated climate change itself but focusing on a narrower space. Flood *et al* (2018) reviewed 43 research outputs reporting game-based interventions for adaptation and concluded that achieving social learning outcomes was aided by factors such as trust between the actors involved, debriefing and evaluation, and the experience and knowledge of facilitators. Rajanen and Rajanen (2019) addressed climate change communication for public engagement using games and gamification but yielded a smaller sample. The 14 papers examined in their review reported overall positive results in terms of game effectiveness, but indicated a lack of quantitative, controlled experiments, and longitudinal studies that would provide more solid evidence.

This review aims at extending these reflections by examining the extant empirical literature on game-based climate change engagement. We aim to analyze the described interventions in four areas, each one connected to a research question exposed in section 2:

- (a) Contexts and populations, including location, age, occupation, and previous relationship to climate change and related topics.
- (b) Intervention design, including player roles, delivery method, format and length, application domain and topics, and game elements that 'structure games and aid in inducing gameful experiences within the systems' (Koivisto and Hamari 2019, p 193).
- (c) Engagement results, including 1. cognitive, affective and behavioral engagement with climate change, and 2. psychological experience with the games themselves, contextualized through data collection and analysis methods.
- (d) Quality appraisal and internal validity, hereafter referred to as 'strength.'

The results serve as the basis for a research agenda that offers scholars in this space current gaps and questions that will lead to new research avenues. The paper is structured as follows. Section 2 describes the systematic literature review process followed, including study planning, literature selection and data extraction. Section 3 reports the results from the 64 research outputs that were finally selected, including bibliographic data and variables organized in the four aforementioned areas. Section 4 presents the research agenda building upon the findings. Section 5 concludes the paper.

2. Methods

This study uses the systematic literature review approach. Systematic literature reviews 'adhere closely to a set of scientific methods that explicitly aim to limit systematic error (bias), mainly by attempting to identify, appraise and synthesize all relevant studies (of whatever design) in order to answer a particular question (or set of questions)' (Petticrew and Roberts 2008, p 9). Here, we aim to summarize the existing corpus of empirical research on game-based interventions for climate change engagement. By summarizing evidence, we intend to provide an understanding of the state-of-the-art in this area and direct future research by highlighting research and design gaps and opportunities (Paré *et al* 2015).

Furthermore, we aim to qualitatively appraise the studies in order to understand their reported effects. However, although we separately consider designs less prone to biases (such as controlled studies) or otherwise reliable in attributing effects to the intervention (such as before-after studies), we do not limit our sample to those. In being more open, we take into consideration the critical realist approach, acknowledging the value of multiple analysis methods and the fact that interventions are decisively influenced by their context (Paré *et al* 2015). As described by Okoli (2015), the process follows a protocol and consists of

four consecutive stages: planning, selection, extraction, and execution, the fourth leading to the completed review.

2.1. Planning

The first stage starts with identifying the purpose of the study. In this case, we seek to answer the following questions, from which we will derive a future research agenda:

- (a) In what populations and contexts have game-based climate change engagement interventions been applied?
- (b) What types of games and gamification do such interventions implement, and what game design elements do they have?
- (c) What does the literature report about the effectiveness of these interventions regarding engagement with climate change and with the games themselves?
- (d) What is the quality and strength of the results?

Next, a protocol determining the procedures to follow throughout the research process is created. This section takes most of its content from the protocol.

2.2. Selection

The second stage includes the search for literature and the application of a practical screen in order to determine what studies are considered for review and which ones are eliminated before further examination (Okoli 2015). The screening process in this review follows two categories of inclusion criteria, with no additional exclusion criteria applied (e.g. time period):

Content applicability criteria:

- (a) The source includes a description of a game-based intervention intended to engage a population with climate change through climate science knowledge, mitigation or adaptation practices, or reports outcomes regarding climate change engagement resulting from a game-based intervention.
- (b) If the goal is to promote mitigation or adaptation practices, they must be explicitly connected to the larger context of anthropogenic climate change.
- (c) The intervention reports empirically derived results.

Format criteria regarding the language and publication forum:

- (a) The source is in English.
- (b) The source has been published in a peer-reviewed journal, conference, or book.

The search process consists of automated database search combined with a forward snowball sampling of the studies that comply with the exposed criteria. The database search employed six relevant databases (Scopus, Web of Science, EBSCOhost GreenFILE, ProQuest Central, IEEE Xplore, and Google Scholar), yielding a total of 1453 results. See supplementary file S1 (available online at stacks.iop.org/ERL/16/063004/mmedia) for a detailed breakdown.

The basic search string used is the product of our knowledge from past research on this field, which includes both climate change and game-based interventions, an iterative search refinement process through diverse pilot searches, and familiarization with the unique requirements and limitations of each database. Due to technical limitations, the string was in some cases divided or otherwise adapted to produce the desired results:

('climate change' OR 'global warming' OR pro-environmental OR (environment* OR ecolog* AND sustainab*) OR greenhouse OR low-carbon OR 'energy efficien*' OR 'energy consum*' OR 'circular economy' OR 'recycl*' OR 'extreme weather' OR 'extreme event' OR 'environmental acti*') AND (gamif* OR 'game-based' OR 'board game' OR 'card game' OR 'video game' OR videogame OR 'digital game' OR 'mobile game' OR 'online game' OR 'computer game' OR 'serious game' OR 'educational game' OR 'role-playing game') AND NOT 'game theor*' AND NOT computing.

Our inclusive approach aimed at narrowing down the results through the practical screen step. However, the refinement process led us to exclude from the search string terms such as 'climate emergency' or 'climate crisis' which did not yield any significant result not covered by other words, and 'gaming,' which introduced hundreds of irrelevant results. Given the amount of noise related to mathematical game theory and purely technical efficiency interventions (for example, algorithms for reduced screen energy consumption), we explicitly excluded two terms ('game theor*' and 'computing') from the search results.

The database search was conducted on 12 February 2020. After aggregating the search results and removing duplicates, two researchers conducted the screening process in two stages:

- (a) The title and abstract of the retrieved studies were reviewed to reject the irrelevant papers. If needed, the reviewers skimmed over the full text.
- (b) The retained papers were read in full and reviewed against the inclusion/exclusion criteria.

The two researchers screened the papers independently and met to compare the results in each of the two stages. Any disagreements in the process were discussed until a consensus was reached, and various iterations were completed to ensure that the

entire sample was examined following the same criteria. Disagreements were fundamentally connected to two aspects: the boundaries of what a game-based intervention is, and what constitutes an empirical intervention. Disagreements were solved by being inclusive in our definitions: game-based interventions include playful events such as role-plays, game jams, and gamified participatory processes, while it was established that any study that includes data from participants, regardless of the level of detail reported, would be included, since this review includes a quality analysis not as a screening mechanism but as a method to answer its fourth research question. The outcome of the process was the list of primary studies to be reviewed systematically. The narrowing down process is shown in supplementary file S1. Once we identified the initial set of 51 primary studies, we conducted a forward snowballing process between 25 March and 6 May 2020 to detect further relevant studies citing them. This resulted in 547 articles to screen as described above. The full narrowing down process for the snowball sample, also presented in supplementary file S1, yielded 13 additional primary studies. Thus, in total we retained for systematic review 64 research outputs (supplementary file S2).

2.3. Extraction

The data extraction process aims at identifying features of interest in the papers reviewed in order to answer the research questions. While the units of analysis were determined beforehand, some specific values were discovered during the data extraction. The process was performed by the same two researchers in charge of the screening process, first independently and then aggregating the findings. The disagreements in coding were discussed until a consensus was reached. The variables were classified in five categories (one for bibliographic classification and four for answering the research questions including the quality assessment). Supplementary file S3 includes the database that serves as the basis for the results.

In summary, we complement previous reviews (Flood *et al* 2018, Rajanen and Rajanen 2019) with the following contributions to the process: comprehensive search phrase, broad database covering, and extensive snowball article sampling. Our research aims also differ from the previous reviews as we systematically examine not only outcomes, but also participants, contexts, and design features of the interventions, whether they address mitigation, adaptation, climate science, or other related topics. In addition, we exclusively consider studies that frame interventions within the phenomenon of anthropogenic climate change, regardless of the proximity of the mitigation or adaptation issues that players encounter in the games (e.g. saving energy or adapting to local floods). Although engagement strategies can address one or more dimensions (Whitmarsh *et al* 2011), policies risk failure and rejection when

the public lacks understanding about climate change (Lorenzoni *et al* 2007). Given the fact that climate change requires not only bottom-up behavior change but also the acceptance of top-down initiatives, we focus on game-based approaches that can contribute to climate change understanding by relating personal issues to their broader context.

3. Results

In this section, we report the results from the data analysis of the 64 empirical research outputs. The results begin with identification and bibliographic data, followed by four sections that address the research questions: population and context (RQ1); intervention and game elements (RQ2); engagement results (RQ3); and quality and strength (RQ4).

3.1. Identification and bibliographic data

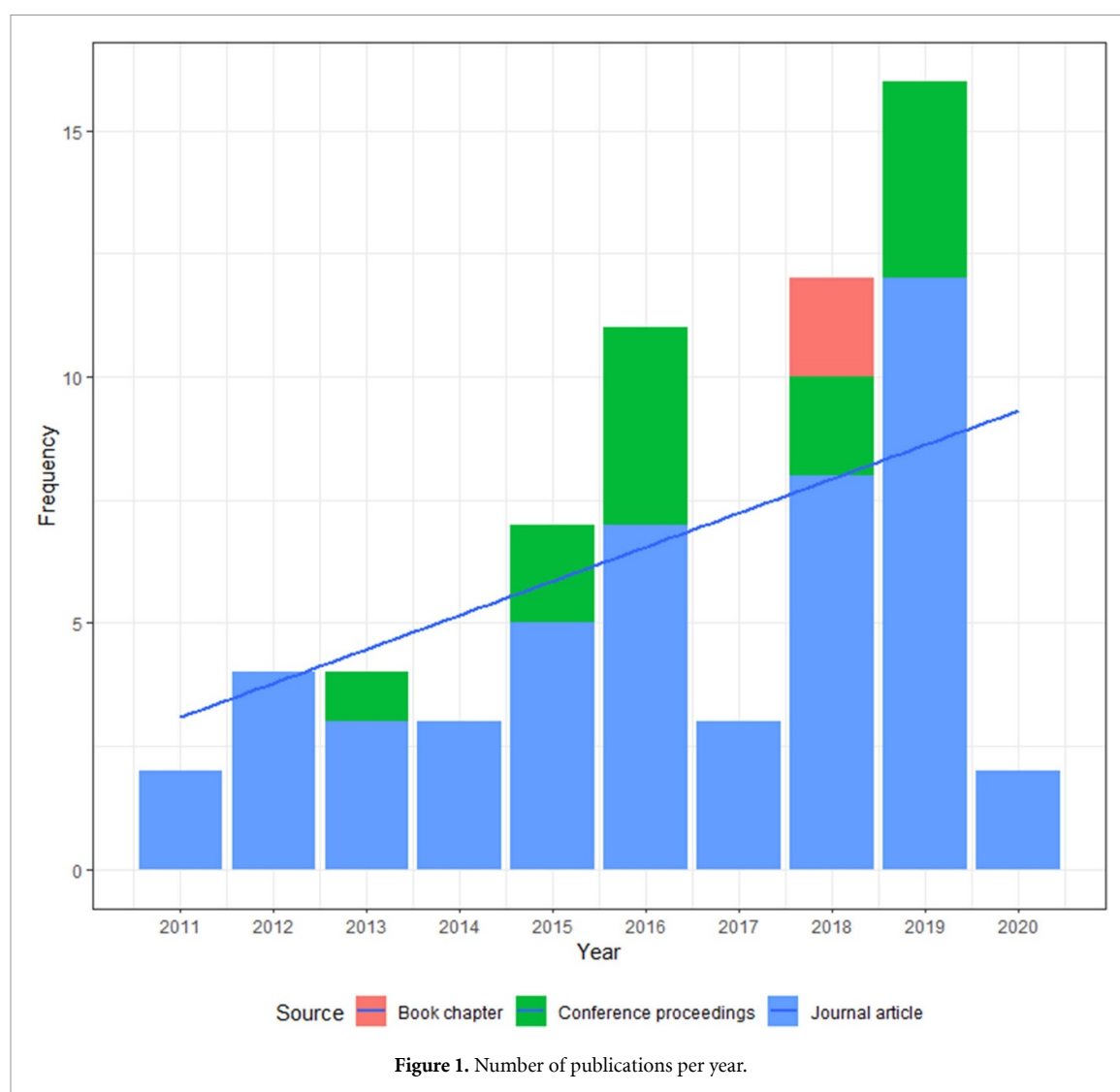
By year of first appearance online, the first papers in the area delimited by our search process were published in 2011. The number remained relatively stable with two to four papers per year until 2014. Since then, we observe an upwards trend with a peak in 2019, with 16 articles published (figure 1). The year 2020, with two publications at the moment of data collection, is incomplete.

Most papers, 76.6%, were published in academic journals, followed by conference proceedings (20.3%) and book chapters (3.1%). We identified 51 individual venues of which five have published more than one paper: Simulation & Gaming (7), Sustainability (4), Environmental Science & Policy (3), the International Journal of Environmental and Science Education (2), and the Journal of Science Communication (2).

To map the research outputs by scientific field, we used the subject-area tags associated with their publication venues in Scopus, where the same venue (including journals, conferences, and books) can be assigned to more than one field. However, only 75% of the papers were indexed by Scopus; thus, this analysis does not fully cover the sample. The most frequent fields were Environmental Science (24 papers) and Social Science (23), followed by Computer Science (13 papers), Business, Management and Accounting (11 papers), Engineering (9), Energy (6) Mathematics (4), and Earth and Planetary Sciences (2). Other tags had only one paper associated.

3.2. Population and context

Our first research question aims to characterize the populations that game-based interventions for climate change engagement target, as well as their contexts. We examine geographical location, age, occupation, and previous relationship to climate change and related topics.



3.2.1. Location

The main countries when considering first authors' affiliation are the Netherlands (with 18.8% of the papers, two thirds of which include adaptation in rivers as an important topic) and the US (17.2%). Nine other countries have more than one paper associated: Germany and the UK (7.8%); Norway and France (6.2%); Spain (4.7%); and Sweden, Canada, Austria, and Brazil (3.1%). When classified by country of intervention, papers exhibit a similar pattern to that of first authors' affiliations, with the US (17.2%) and the Netherlands (10.9%) being the most recurrent (figure 2). In cases in which the country was not reported but the intervention was in a physical space and all authors were from the same country, that was assumed to be the place of the intervention. Some papers (4.7%) described interventions distributed online, so the country was unknown and possibly multiple.

While 70.3% of the papers placed their interventions in advanced economies, only 26.6% included emerging and developing economies, according to the classification by the International Monetary Fund

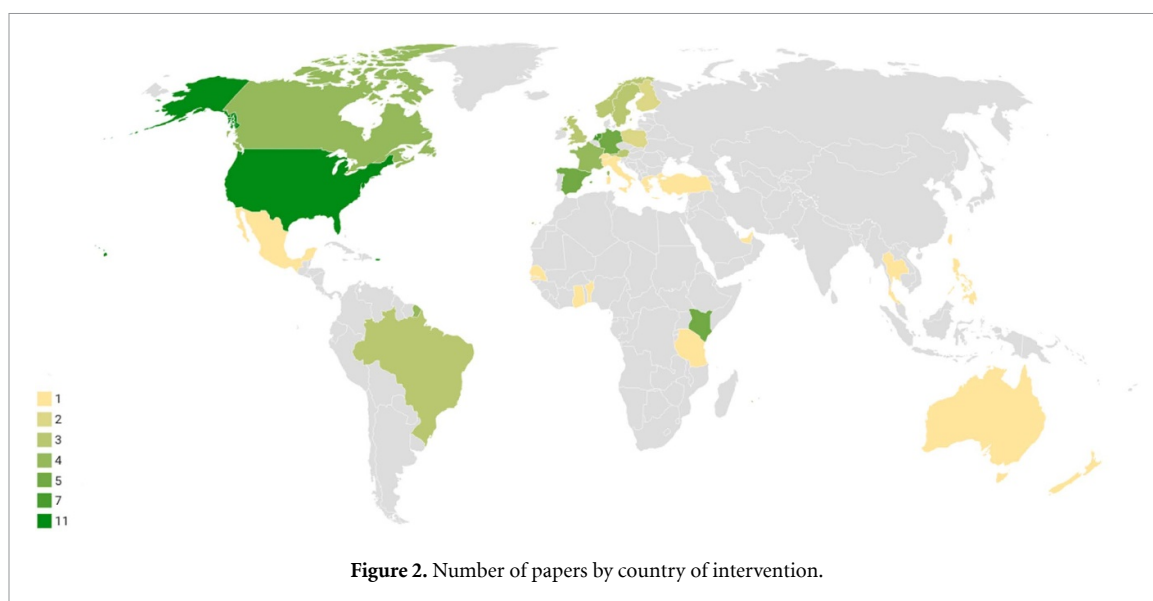
(2020). Three emerging countries had more than one research output: Kenya (7.8%), Brazil (4.7%), and Poland (3.1%). By continents, 50% of the research outputs included countries in Europe, 29.7% America, 12.5% Africa, 9.4% Asia, and 3.1% Australia or New Zealand.

3.2.2. Age and gender

In terms of age, 60.9% of the studies had adults as the only participant population. Participants under 18 years were the sole target in 23.4% of the studies, while 6.2% included both adults and minors. Another 9.4% did not report the participants' age groups. In contrast, 73.4% did not report the participants' sex or gender. Of those that reported this data, 47.1% presented samples with male preponderance (over 60%), 35.3% had between 40% and 60% of males, and 17.6% had more than 60% of females.

3.2.3. Occupation

By occupation, students, especially in tertiary education, were the most targeted population (table 1). Overall, 53.1% articles involved K-12 students (in

**Table 1.** Number of papers by occupation.

Occupation	Frequency
Students (tertiary)	19
Students (K-12)	16
Farmers, fish farmers and farming stakeholders	12
Other professionals or unreported	11
Regional or national policymakers and decision-makers	8
Academics or educators	7
Local policymakers and decision-makers	6
Local citizens and other local stakeholders	5

primary or secondary education, usually between 5 and 18 years old), tertiary students, or both in one case, while 40.6% included professionals, academics, or stakeholders related to the topic of the intervention. Meanwhile, 17.2% included subjects whose occupation was unknown, unreported or not connected to the intervention topic or unique to one study (e.g. game developers or university staff). The total number surpasses 64 because papers often had more than one type of audience.

3.2.4. Previous relationship to climate change and related topics

Of the 64 research outputs, 40.6% did not report any previous contact or interest of the participants with climate change or related topics. In contrast, another 40.6% included participants who had a direct professional or (assumedly voluntary) educational involvement with the topic. Furthermore, 15.6% captured the participants' engagement with climate change prior to the intervention, where most participants reported a positive degree of involvement in at least one of the measured dimensions (beliefs, concern, knowledge). A generalized lack of awareness or

interest in the topic of the intervention was reported in 3.1% of the papers.

3.3. Intervention content and design

To answer our second research question, related to types of gamification and their design elements, we analyzed how interventions characterize players; their delivery method; the game format, based on how technology is used; the duration of the intervention; the spatial scope of the intervention; the game topic, and the game elements. It is worth noting that, while the reviewed papers mentioned 56 unique games and gamified strategies, eight games appeared in more than one paper: WeShareIt (5), Keep Cool (3, including a digital version), Sustainable Delta (3), Forage Rummy (3), Catan (with the Oil Springs and Global Warming expansions) (2), two Future Delta iterations (2), Grazing Game (2), and The Maladaptation Game (2). Overall, we found very few of the reviewed game-based implementations to be accessible online in a digital format at the time of analysis. Of those available, some were commercial releases (Waddington and Fennewald 2018, Fjællingsdal and Klöckner 2019).

3.3.1. Player characterization or role

According to Wibeck (2014), engagement initiatives can conceptualize the public in different ways, such as economic actors who could engage in sustainable consumption, potential supporters of climate policy within a representative democracy, or participants in deliberative democratic action through dialog. Based on our analysis, 28.1% of the papers characterized players as consumers, promoting lifestyle changes as a way to act upon the climate crisis, while policy support was only found, rather tangentially, in one article (Hansen *et al* 2018). We found that 43.8% promoted participation in climate science and

policy dialog, but they did so by simulating decision-making processes or affording peer discussion rather than providing a space for binding deliberation. Only one article (Steelman *et al* 2019) combined artistic exhibitions with communication exercises between policymakers and citizens. Beyond these categories, 32.8% engaged players in the context of a professional practice, such as farming, water management or policymaking; three interventions focused on climate science did not discuss an explicit response; and one paper educated on a purely technological solution, carbon capture and sequestration (Feldpausch-Parker *et al* 2013). While professional practice papers were naturally directed at adults, as were simulated participation papers (71.4% vs. 28.6% that included minors), consumer papers favored minors (55.6% vs. 38.9% that included adults).

3.3.2. Length, facilitation, and format

Most interventions (75%) occurred in a single session, while the rest extended the interaction to multiple moments of contact or allowed independent continued use for a period of time. Most papers, 54.7%, described facilitated interventions, so the players had the assistance of at least one expert that was present, available and participating in some capacity during the intervention. Meanwhile, 43.8% described independent interventions where players interacted with the game and each other largely autonomously. One additional study used both methods (Illingworth and Wake 2019). Most interventions that included simulated participation (63%) were facilitated, as were almost all that promoted professional practice (85.7%). Conversely, 77.8% of interventions that promoted a lifestyle change were meant to be used autonomously.

Game experiences adopted three main formats: digital, analog, and hybrid. The latter combined analog and digital approaches, e.g. role-plays supported with modelling software. In total, 26 digital games, 21 hybrids and 19 analog tabletop or role-playing games were described, including two that could be played both as a digital and board game (Erb 2015, Ouariachi *et al* 2019), totaling to 66 games. Two articles reported using two very similar games each (Rumore *et al* 2016, Gugerell *et al* 2018), which are combined for the purposes of this review.

Table 2 shows how different game formats were delivered; one analog game was offered with and without a facilitator in the same study (Illingworth and Wake 2019). Thus, the total number of individual game deliveries in the table is 67.

3.3.3. Application domain

The research outputs were classified in three application domains: those describing interventions focused on increasing knowledge about climate change from

Table 2. Game formats and delivery methods.

	Digital	Hybrid	Analog	Total
Facilitated	3	20	13	36
Independent	23	1	7	31
Total	26	21	20	67

a climate science perspective (45.3%), on mitigation practices (59.4%), and on adaptation (53.1%). Most articles featured a single application domain, but combinations were also common (figure 3). Most papers with tertiary students focused on mitigation (84.2%), while those addressing climate science (52.6%) and/or adaptation (47.4%) were less frequent. Most interventions directed at K-12 students aimed at increasing climate science knowledge (87.5%) and mitigation behavior (75%), as did the ones with unreported or general public (63.6% and 100%, respectively). Papers including local citizens and stakeholders, policymakers, academics, or farmers almost always considered adaptation. In terms of player roles, mitigation was observed in all but one of the papers that framed the player as a consumer and promoted a lifestyle change, and in 88.9% of the papers that defined the player as participant in science or policy discussion. In contrast, adaptation was addressed in 95.2% of the articles that framed the player as a professional practitioner.

Regarding spatial scope, the most frequent framing of the topics represented was global. Yet, diversity is large (table 3). Articles with a multiple scope often related high-level general climate concepts to specific local and individual situations.

3.3.4. Game topics

Topics were directly coded from the reviewed literature, where often more than one topic is presented at once. Usually, climate science knowledge was related to its basic concepts related to climate change, for example the carbon cycle, as well as other scientific aspects of climate change (e.g. impacts on biodiversity). In the 34 adaptation papers, droughts and floods were the most common impacts (see table 4). Of the 38 mitigation papers, 76.3% considered it from an economic point of view (that is, as an issue involving production and consumption of energy and other goods and resources) and 47.4% involved policymaking, regulation and political negotiation, which can also affect the economic side.

3.3.5. Game elements

Games contain identifiable elements that generate the play experience (Koivisto and Hamari 2019). In this study, we have based our classification on that of Koivisto and Hamari (2019), but have included additional elements detected through the data extraction process and reorganized or deleted others previously

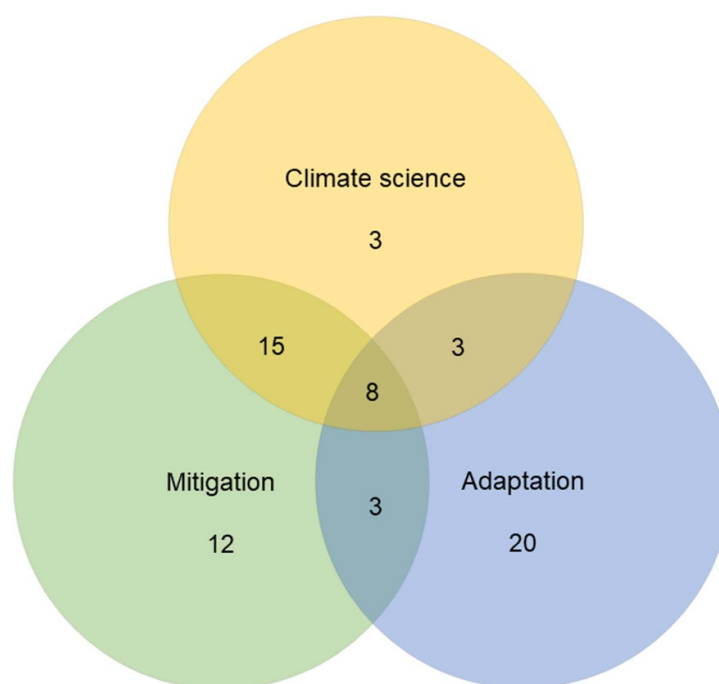


Figure 3. Number of articles by domain represented.

Table 3. Spatial scope.

Spatial scope	Climate science	Mitigation	Adaptation	Total
Global	11	13	3	27
Multiple	12	5	0	17
Water environments (coasts, rivers, lakes)	3	0	12	15
Farms and fish farms	0	2	11	13
Households or individual actions	0	9	1	10
Human settlements (cities, towns)	1	5	4	10
Countries and regions	1	2	2	5
Other professional environments	1	2	1	4
Total	29	38	34	101

Table 4. Climate science, mitigation, and adaptation topics by number of research outputs.

Topic	Climate science	Mitigation	Adaptation	Total
Economic mitigation	0	29	0	29
Generic awareness or climate science	24	0	0	24
Droughts	1	0	22	23
Policy-based mitigation	0	18	0	18
Floods	1	0	11	12
Unspecified or other climate impacts	5	0	6	11
High or rising temperatures	7	0	3	10
Sea level rise	6	0	4	10
Heavy precipitation	1	0	2	3
Pests and weeds	0	0	3	3
Storms	2	0	1	3
Threats to ecosystems	3	0	0	3
Desertification	0	0	2	2
Heatwaves	1	0	1	2
Prolonged growing season	0	0	2	2
Water quality	0	0	2	2
Weather variability	0	0	2	2
Ocean acidification	1	0	0	1

Table 5. Game elements' classification and frequency.

Game elements	Frequency
Achievement/progression-oriented	273
Challenges, quests, missions, tasks, clear goals	63
Levels (segmentation of gameplay into rounds, levels, missions...)	58
Performance and progress stats and feedback	56
Increasing difficulty	17
Points, score, experience	35
Quizzes, questions	15
Timer, speed	14
Leaderboards	9
Badges, achievements, medals, trophies	4
Player levels, unlockable skills and resources that the player keeps	2
Social-oriented	97
Cooperation, teams, collaboration	44
Competition, possible tension between diverging or conflicting interests	33
Customization, personalization	10
Peer-rating, also betting to review work of others	4
Social networking features (contact with non-players)	3
Collective voting	3
Immersion-oriented	114
Game world (visual representation)	48
Role play (interaction characterized as a fictional character, especially with other players)	24
Narrative, narration, storytelling, dialog with fictional characters	20
Avatar, player character, virtual identity	19
In-game rewards (obtained for performance, aside from points and badges)	3
Representation, resources, materials	180
In-game economy (a market where the player can at least buy goods)	28
Debriefing by facilitators	25
Physical playboard	25
Physical objects as game resources	19
Physical random number generation (dice)	11
Facilitators (with no debriefing)	11
Physical cards as resources	11
Physical cards as actions	8
Physical cards as events and challenges	8
Unexpected events with odds unbeknownst to players	9
Digital objects as game resources	6
Digital random number generation	5
Real-time dependence	5
Digital cards as actions	3
Digital cards as events and challenges	3
Connection to IoT devices	1
Real world interactive objects (for use with digital platform through direct interaction)	1
Physical cards as identity	1

classified as 'miscellaneous' in order to leave only four meaningful categories: elements that allow or quantify player achievement and progression through the system; elements that support social relationships; elements that uphold a sense of immersion in the game; and materials or resources (digital, physical or human) that represent other game concepts. In some cases, additional materials available online, such as design documents, appendices, or videos created by the game developers, have been used to clarify the meaning of certain elements. For this analysis, we consider Erb's (2015) two conditions as two separate games due to reported design differences, while Ouariachi *et al*'s (2019)

game is understood as a single tabletop game due to lack of explanation in the original source. Another article that uses two tabletop games (Gugerell *et al* 2018) has also been considered as one item due to lack of detailed differentiation. Thus, the total number of games for design element analysis is 65.

All games described in the sample included at least one achievement-oriented element. This category was followed by immersion (81.8%), representation resources and materials (81.8%), and social (76.9%). Table 5 details the individual game elements within these categories and their number of occurrences in the reviewed literature. The reviewed

Table 6. Presence of element types by game format.

	Achievement	Social	Immersion	Representation, resources, materials	Total
Digital	25	11	20	14	25
Hybrid	21	21	17	21	21
Analog	19	18	17	19	19
Total	65	50	54	54	65

Table 7. Number of papers reporting engagement results (including all directions: positive, mixed and negative) by dimension and specific outcome.

Engagement dimension	Number of papers	Specific outcome	Frequency
Cognitive	50	Climate science knowledge	26
		Mitigation knowledge	21
		Adaptation knowledge	20
Affective	24	Individual affect (e.g. interest, responsibility, motivation, confidence, empowerment, importance of personal behavior change)	19
		Concern about climate change and its risks	6
		Collective affect (e.g. importance of cooperation, trust)	6
		Empathy for or understanding of others	3
		In-game dialog, cooperation, and competition	21
Behavioral	35	Personal mitigation behavior	8
		Produced outputs (e.g. games, adaptation plans)	8
		Personal involvement with study and information	3
		Community real-world decision-making	2
		Preference and other benefits	21
Game experience	41	Enjoyment, fun, motivation	18
		Game experience issues	13
		Intense participation	7

game-based designs almost ubiquitously relied on three achievement elements: challenges and clear goals, levels, and performance and progress statistics and feedback. Those that included social features exhibited cooperation-oriented elements more commonly than competition, but they are often combined. Immersion-wise, many chose to represent in-game worlds, either fictional or based on real spaces, visually.

When classified by format (table 6), digital experiences tend to lack social elements (in this sample, mainly cooperation and competition), while hybrid and analog games are usually designed as social activities. Representation, resource and material elements, which usually refer to facilitators and physical objects but include digital representations of physical objects as well, are also higher in hybrid and analog games.

3.4. Engagement results

Our third question relates to intervention effectiveness. Our definition of effectiveness broadly encompasses any reported results evincing engagement with climate change or the games themselves. After extracting evidence of climate change engagement, or reported lack thereof, we classified each result in the three categories described by Lorenzoni *et al* (2007): cognitive, affective and behavioral. In addition, we collected evidence related to engagement with games themselves, also called ‘psychological outcomes’ in

gamification literature (Koivisto and Hamari 2019). Other findings presented in the papers, for example those related to games uncovering what participants already do in their lives, were not considered in this review. Consequently, we only report data collection and analysis methods used to uncover engagement. We also classify papers according to the direction of their results, either positive (engagement was reported), mixed (engagement results were reported but they were weaker than hypothesized, conditional, or limited by negative effects), or negative (indicators of disengagement were reported), taking separate note of results from statistical tests.

As depicted in table 7, the most reported form of engagement is cognitive, followed by experiences with the games. In some cases, a paper reported multiple specific outcomes within the same dimension (e.g. knowledge about climate science and mitigation topics). While cognitive engagement results are balanced in terms of the three application domains, most affective results represented generally positive changes in players’ emotional relationship towards climate change and their own actions (increased interest, increased appreciation of the environment, reduced fatalism, a sense of empowerment, responsibility, motivation to act in the future, or perceived importance of their own behavior change). As shown in table 7, the most reported behavioral engagement results consist of dialog between players and actions

Table 8. Direction of results by engagement dimension.

Engagement dimension	Number of papers	Qualitative or descriptive results			Statistical results		
		Positive	Mixed	Negative	Positive	Mixed	Non-significant
Cognitive	50	37	3	0	11	0	2
Affective	24	14	2	1	6	1	1
Behavioral	35	29	3	0	3	1	0
Game experience	41	27	9	3	1	1	0

Note. The number of papers is higher in the results section than in the overall count because five papers reported more than one type of result in the same engagement dimension. One paper reported both statistically positive and mixed cognitive results; two reported statistically non-significant and positive cognitive results; one reported statistically non-significant and positive affective results; and one reported statistically positive and positive behavioral results.

Table 9. Results by data collection method.

Data collection method	Frequency	Engagement dimension			
		Cognitive	Affective	Behavioral	Game experience
Questionnaire	39	29	19	10	18
Observation, including recordings, notes, and non-systematic data-logging	23	12	2	14	9
Debriefing, focus group or panel discussion	17	13	2	4	6
Data log from gameplay and outputs	13	7	0	10	1
Interview	12	9	4	4	5
Unknown	4	2	1	1	3
Concept mapping	2	2	1	0	0
Essay or presentation	2	2	1	2	1

such as cooperation and competition within the context of the game.

In all four types of engagement measured, most results are positive or statistically positive (table 8). Game experience is the only dimension with a relatively large number of mixed results (24.4%). No article reported effect sizes for statistically non-significant results.

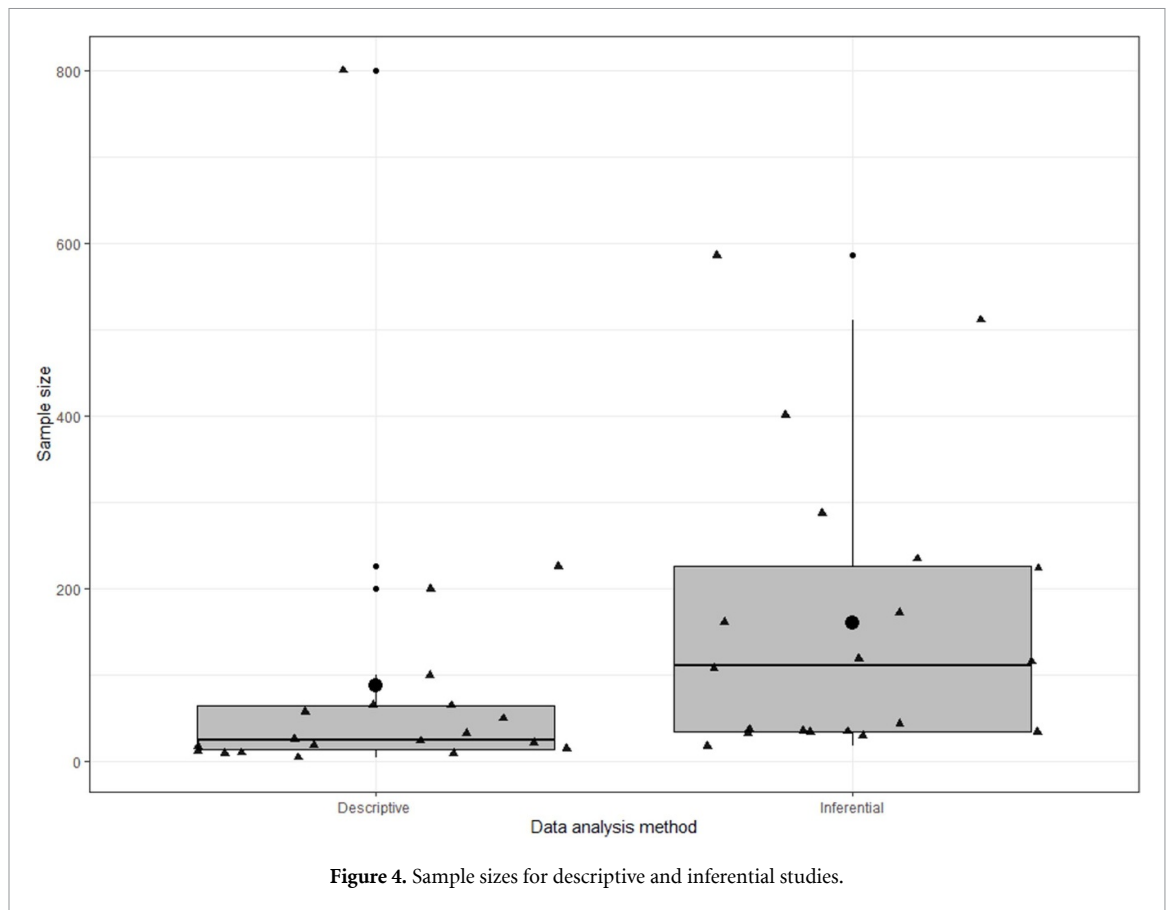
Although infrequent, non-positive results can be found across the three climate change engagement dimensions and especially in game experiences. The reported cognitive issues include, for example, mistrust and rejection of game models (e.g. Waddington and Fennewald 2018). Affective issues include induced fatalism due to extreme difficulty (Waddington and Fennewald 2018) and a decrease in trust in others as a result of game interaction (Onenican *et al* 2018), as well as failures to significantly increase self-efficacy or pro-environmental motivation (e.g. Ouariachi *et al* 2018). Regarding behavioral outcomes, some papers report e.g. limited behavior change (Waddington and Fennewald 2018), lack of interaction with science materials (Foltz *et al* 2019) or limited in-game cooperation (Onenican and Van de Walle 2017). Finally, game engagement issues often refer to perceived confusion or complexity (e.g. Illingworth and Wake 2019) and lack of freedom,

enjoyment or challenge (e.g. Fjællingsdal and Klöckner 2019), to name the two most common.

It must be acknowledged here that no studies in the sample reported offering external incentives for real-world mitigation or adaptation behaviors. One paid study (Waddington and Fennewald 2018) offered an economic incentive to players that won the in-game scenario, which could have encouraged a participant to reportedly hack the game in order to be able to understand its system better and complete the task, but this reward was exclusively tied to the (digital, single-player) game. In another, students of a gamified course were rewarded with bonus points in their grades for studying in advance (Toriz 2019), which should be considered in relation to their reported increase in advance study and higher grades when compared to others receiving non-gamified teaching. Three studies only compensated participants for their participation with the chance to win prizes (Foltz *et al* 2019), a small allowance to cover travel costs and time (Lebel *et al* 2016), and free lunch (Schroth *et al* 2014).

3.4.1. Data collection methods

The data collection methods employed to detect climate change engagement outcomes were analyzed and coded (table 9). Most outcomes resulted from



the use of questionnaires across the categories except behavioral, which was frequently observed or logged. Of the 29 questionnaires used for cognitive outcomes, 41.4% included knowledge questions to assess the participants' learnings beyond self-reports or observations. One interview and one concept map provided similar data.

Figure 4 illustrates the sample size distributions of descriptive studies ($n = 20$, $M = 88.4$, $SD = 178.19$) and inferential studies ($n = 20$, $M = 161.25$, $SD = 168.48$) using boxplots. The sample size for each study is depicted with a triangle and the mean value per category is illustrated with a black dot. The depicted boxplots facilitate a preliminary comparison between the two distributions. More precisely, descriptive studies tend to use smaller samples, while inferential studies tend to have a higher variance but a higher mean value overall.

3.4.2. Data analysis methods

Of all the research outputs, 71.9% analyzed engagement data qualitatively, 31.2% analyzed quantitative data using inferential methods (i.e. statistical tests to examine hypotheses and make deductions), and 32.8% reported descriptive statistics of data. However, papers often mix methods: 37.5% were purely quantitative, 14.1% were purely descriptive, 10.9% were purely inferential, 17.2% mixed qualitative and descriptive methods, 17.2% mixed qualitative and inferential methods, and only two mixed descriptive

and inferential methods. Most data analysis methods are used to report cognitive climate change engagement (table 10).

Of the 24 studies that reported data qualitatively, 23 were case studies; the remaining one was a quasi-experiment that reported engagement data only through debriefing and observation (Dah-gbeto and Villamor 2016). The nine descriptive studies presented four before–after designs and five case studies in which data was collected only during or after the intervention, one of which presented participants with screenshots of an app (Petersen *et al* 2019). The seven inferential papers include five before–after designs, one quasi-experiment that records data during gameplay, and one controlled experiment (Nussbaum *et al* 2015). Of the 11 papers that mix qualitative and descriptive methods, six were case studies that collected data only during and after the intervention, four were before–after designs and one included a control group for comparison (Toriz 2019). The 11 papers using qualitative and inferential methods include one study that measured engagement only after the intervention, six before–after designs and four controlled studies. Two papers present engagement results supported by quantitative data analyzed in descriptive and inferential ways: one is a before–after design (Feldpausch-Parker *et al* 2013) and the other collects gameplay data (Piccolo *et al* 2016). Overall, only 26 studies in the sample include either before–after measurements or a control group.

Table 10. Engagement results by data analysis methods, in number of papers.

Data analysis methods used	Number of papers	Engagement dimension			
		Cognitive	Affective	Behavioral	Game experience
Qualitative	24	19	5	15	15
Descriptive	9	8	5	4	6
Inferential	7	5	2	2	1
Qualitative and descriptive	11	9	3	7	10
Qualitative				1	4
Descriptive		5	2	2	3
Qualitative and descriptive		4	1	4	3
Qualitative, descriptive, and inferential	11	7	9	6	7
Qualitative			3	2	5
Qualitative and descriptive		1		2	2
Qualitative and inferential		2			
Inferential		3	5	2	
Inferential and descriptive		1	1		
Descriptive and inferential	2	2		1	2
Descriptive		1		1	1
Inferential		1			1

Note. Some papers with qualitative and inferential methods include descriptive data as support.

Furthermore, only five articles in the total sample measured some form of climate change engagement beyond immediately after the intervention.

3.4.3. Engagement findings in high and medium strength papers

In this sample, 40.6% of the papers have been classified as of high or medium strength due to their designs, which provide stronger evidence of game effects on climate change engagement (see section 3.5). Twenty compare before and after measurements, while six include control groups. Of the six papers with control conditions, two compared games with other media containing equivalent climate change information (Smith *et al* 2019, Toriz 2019). The rest involved ‘not playing’ (Ouariachi *et al* 2018), a non-climate change related science website (Nussbaum *et al* 2015), the same game with different settings (Van Pelt *et al* 2015), and a non-climate change game (Waddington and Fennewald 2018). Another study that tested the same game in board and digital format using diverse player groups (Erb 2015) was considered a qualitative paper due to it having different before and after measurements, which were presented qualitatively, and allowing part of the players to experience both conditions, thus it is not included here.

In terms of data collection, these studies use 64.1% of the questionnaires in the sample but only 35.3% of debriefs, 33.3% of interviews, 30.8% of data logs, and 29.4% of interviews. Regarding data analysis, four report findings using descriptive methods, one uses descriptive and inferential, five qualitative and descriptive, six inferential, and ten qualitative and inferential. As can be seen in table 11, cognitive and affective outcomes are often measured statistically, while reports on behavioral and game engagement are often either qualitative or descriptive.

Here, we examine their outcomes in more detail, including possible connections between results and specific game elements. One ideal approach to understand the effects of isolated game features would be the value-added game research paradigm, since it compares two player groups, one with a base game and another playing the same game with one specific element added (Mayer 2019). Regrettably, none of the papers adopted such an approach. However, we can still establish qualitative connections between reported game elements and results, indicating how different features can enable the changes observed, although it must be acknowledged that no comparison of the same intervention without those elements exists. In addition, supplementary file S4 shows the relationships between engagement results and game elements.

3.4.3.1. Cognitive engagement

Of the 20 research outputs that reported cognitive engagement-related results, 12 employed questionnaires or concept map assignments that tested participants’ knowledge. This represents 85.7% of all test-like methods used in the sample. Through this assessment method, games have been found to increase cognitive engagement with climate science, mitigation, and adaptation. Climate science topics include, for example, climate literacy (e.g. Harker-Schuch *et al* 2020), knowledge regarding global change (Pérez-Fernández *et al* 2019), climate change causes, impacts and solutions (Angel *et al* 2015), and overall understanding of climate change as a systemic phenomenon (Waddington and Fennewald 2018). In some cases, however, studies failed to report statistically significant results (e.g. Van Pelt *et al* 2015) or authors noted that learning outcomes depended on the players’ acceptance level of the game modeling of climate change (Waddington and Fennewald 2018). Cognitive engagement about mitigation included

Table 11. Results from high and medium strength papers.

Engagement dimension	Number of papers	Qualitative or descriptive results			Statistical results		
		Positive	Mixed	Negative	Positive	Mixed	Non-significant
Cognitive	20	11	1	0	9	0	2
Affective	16	7	1	1	6	1	1
Behavior	12	8	1	0	3	1	0
Game experience	16	10	4	1	1	0	0

topics such as energy use (Toriz 2019) and carbon capture and sequestration (Feldpausch-Parker *et al* 2013). Participants were also engaged with adaptation through water conservation (Nussbaum *et al* 2015), and water management in situations of flood and drought risk (Bathke *et al* 2019).

Other assessment methods have also been used to report engagement with all three aspects: climate science, articulated in sustainability awareness (Chappin *et al* 2017), knowledge about climate risks (Rumore *et al* 2016), and climate consequences (Hoyos *et al* 2019); mitigation, including energy transition concepts (Ouariachi *et al* 2019), the impact of personal actions (Lee *et al* 2013), and the importance of sharing wealth between nations (Scarlatos *et al* 2013); and adaptation through topics such as cooperation (Onencan *et al* 2019) and situational awareness (Onencan and Van de Walle 2018).

As occurs with the overall sample reviewed, the vast majority of these interventions seemed to rely on game elements related to player achievement: a goal was the basic building block for players to engage with learning content. The majority used challenges with an explicit score, gameplay segmentation and performance feedback. Some studies added other achievement features to support cognitive engagement, such as quizzes (e.g. Harker-Schuch *et al* 2020), or complemented challenges with an increasing difficulty progression (e.g. Pérez-Fernández *et al* 2019) or timers (Bathke *et al* 2019).

However, the corpus indicates that certain cognitive outcomes may be connected with other specific game elements. In some cases, it seems crucial to immerse the action in a known environment (e.g. Nussbaum *et al* 2015). Other games brought abstract climate science to life through immersive elements such as avatars, stories and characters, and visual worlds (e.g. Harker-Schuch *et al* 2020). When preventing the tragedy of the commons, collaboration and competition in the face of random impacts were key (Chappin *et al* 2017); other games increased awareness of cooperation precisely through multiplayer mechanics (e.g. Onencan *et al* 2019). Achieving learning outcomes through simulated relevant mechanisms also occurred, for example, when teaching about the importance of sharing wealth by using an economy game element (Scarlatos *et al* 2013) or by introducing unexpected climate impacts (Onencan

et al 2019). In class settings, competition for grades can be mirrored in gamified systems (Toriz 2019). Facilitation (Hoyos *et al* 2019) and especially debriefs (e.g. Rumore *et al* 2016) were cited as methods for reflection and sense-making. Few games employed customization (e.g. Yamada *et al* 2019), badges (Toriz 2019), or reward systems (e.g. Waddington and Fennewald 2018). Table 12 summarizes all of the cognitive engagement results, including details about the associated interventions, and the game elements reported in the high and medium strength interventions (for more details, see supplementary files S3 and S4).

3.4.3.2. Affective engagement

Sixteen papers reported affective engagement outcomes. As expected, achievement mechanics, at least missions and feedback, were used throughout the corpus. The importance of a well-balanced challenge is reinforced by the experiences in Waddington and Fennewald's (2018) study, where excessive difficulty led to fatalism. However, other elements besides the achievement group can be connected to affective engagement. For example, immersive games with avatar-supported role-plays (Rumore *et al* 2016) or avatars within a story-driven local, visual game world (e.g. Angel *et al* 2015) were found to increase concern. In addition, Schroth *et al*'s (2014) intervention increased perceived local responsibility and support for more radical policies. Challenges situated in visual local environments raise interest in water conservation (Nussbaum *et al* 2015). Including uncertain climate impacts favored responsibility towards the climate (Meya and Eisenack 2018) and was described as 'psychological(ly) strong' (Van Pelt *et al* 2015, p 46).

Social elements were one important category for affective results. Multiplayer role-plays seemed to enable empowerment (e.g. Rumore *et al* 2016) and other social experiences brought personal attitude changes towards sustainability or the environment (e.g. Chappin *et al* 2017). Social games resulted in motivation to teach and discuss with others (e.g. Lee *et al* 2013) or research topics discussed in the game (Hoyos *et al* 2019). However, issues with graphics and perceived lack of interactivity in a digital experience played in pairs brought non-significant increases in

Table 12. Presence of game elements and cognitive engagement results in high and medium strength papers.

Game elements	Cognitive engagement results
Achievements/progression Challenges (20); feedback (19); levels (18); points (14); quizzes (7); increasing difficulty (6); timers (5); leaderboards (4); badges (4). Social Cooperation or collaboration (13); competition (9); customization (3); peer-rating (2); collective voting (1). Immersion Visual game world (16); avatar (8); stories or characters (8); role-play (6); in-game rewards (2). Representation, resources, materials Debriefing (7); physical playboard (6); in-game economy (6); physical or digital objects as game resources (5); unexpected events (3); real-time dependence (2); randomness (1); facilitators (1).	Engagement with climate science <ul style="list-style-type: none"> • Retention of climate change causes and local impacts; increase in knowledge about the carbon cycle and other climate science topics; improvement in climate literacy through single-player digital games; increased understanding of coastal ecosystems and conceptual broadening of climate change; learning about climate change science concepts; and knowledge about basic concepts of climate change (single-player digital games, K-12 students) • Increase in understanding about global change (multiplayer board game, K-12 students) • Positive change in awareness and understanding of sustainability issues (observed, but the game's effects on knowledge are non-significant) (multiplayer board game, adults) • Increased knowledge of climate change causes, dynamics, and impacts (hybrid role-play, K-12 and tertiary students) • Increased understanding of climate change as a system (single-player digital strategy game, players' background unknown) • Better understanding of the environmental crisis and its consequences (multiplayer hybrid simulation gamifying a course, tertiary students) • Increased awareness of climate change risks at the local level (role-play simulations, local stakeholders) Engagement with mitigation topics <ul style="list-style-type: none"> • Retention of possible local climate change solutions; knowledge about carbon capture and sequestration; and learning about personal actions for mitigation (digital single-player games, K-12 students) • Increased academic performance in a course about energy use (gamified flipped classroom, tertiary students) • In-game fight against the tragedy of the commons (multiplayer board game, adults) • Understanding how personal actions affect global warming (gamified digital app, tertiary students) • Increased awareness about local energy transition and the need for collaboration (analog and digital game played in groups, K-12 students) • Knowledge about country-level mitigation measures and awareness of the importance of sharing wealth internationally to combat climate change (multiplayer digital simulation, tertiary students) Engagement with adaptation topics <ul style="list-style-type: none"> • Knowledge on aspects of water quality and mitigating droughts and floods in the context of water management (hybrid multiplayer game, multiple stakeholders) • Water conservation knowledge, abandoned misconceptions related to weather and climate and the ozone layer (single-player digital game, K-12 students) • Learning about water cooperation and team interdependence; and significant increase in situational awareness (multiplayer hybrid game, decision-makers) • Increased perception that uncertainty complicates preparing for adaptation (role-play simulations, local stakeholders) Issues <ul style="list-style-type: none"> • Diversity in learning outcomes influenced by acceptance of a computer strategy game's simulation model (players' background unknown) • Broader understanding of climate change uncertainty, but learning effect inconclusive (non-significant) (hybrid simulation game, water managers)

self-efficacy and limited willingness to make behavioral changes (Ouariachi *et al* 2018).

Positive social attitudes were related to in-game social actions in some cases. Games where players interact with peers have resulted in increased optimism about international (Meya and Eisenack 2018) or local (Ouariachi *et al* 2019) cooperation, local and personal confidence regarding climate adaptation (Rumore *et al* 2016), increased perception of self-trustworthiness after playing (Onencan *et al*

2018), and perceived importance of cooperation and empathy for other game participants and their viewpoints, and appreciation of different perspectives enacted through role-taking (Rumore *et al* 2016). However, competitive dynamics might have also decreased trust after participating in a multiplayer exercise (Onencan *et al* 2018). Table 13 summarizes all of the affective engagement results, including details about the associated interventions, and the game elements reported in the high and medium

strength interventions (for more details, see supplementary files S3 and S4).

3.4.3.3. Behavioral engagement

Twelve papers reported some form of behavioral engagement, although this often occurred inside the game. In-game discussions could occur through virtual identities and inside a story (Lee *et al* 2013), but social experiences were also common. These resulted in social learning (e.g. Bathke *et al* 2019), in-game cooperation (e.g. Onencan *et al* 2019), the formation of new professional connections (e.g. Bathke *et al* 2019), and self-reported change of behavior (Chappin *et al* 2017). Translation of game action to community decision-making was observed after role-playing (Rumore *et al* 2016), a similar game was linked to students reducing their carbon footprint (Oliver 2016), and another tied behavior change directly to its mission goals (Lee *et al* 2013). Multiplayer gamification also increased course participation (e.g. Toriz 2019). Indirectly, unexpected climate impacts can be used as symbols to foster climate change familiarity (Onencan and Van de Walle 2018), critical for situation awareness. On a more negative note, fatalism derived from extreme difficulty could be related to lack of behavior change (Waddington and Fennewald 2018). Table 14 summarizes all of the behavioral engagement results, including details about the associated interventions, and the game elements reported in the high and medium strength interventions (for more details, see supplementary files S3 and S4).

3.4.3.4. Game experience

Finally, 16 papers in this subset reported outcomes related to being engaged with the game itself. Although most measured/reported outcomes were positive, including experiences of enjoyment, entertainment, fun, appreciation and general interest and engagement, some players criticized games as inadequate methods to address serious issues (Bathke *et al* 2019), seemed to refuse to engage with some tasks due to them providing little personal value (Piccolo *et al* 2016), reported confusion and excessive difficulty (e.g. Waddington and Fennewald 2018), or criticized games' mechanics, graphics (e.g. Ouariachi *et al* 2018) and technical issues (Yamada *et al* 2019), especially in digital experiences. In these cases, positive experiences seem derived from adequate implementations of game design elements rather than simply using them or not. Players can appreciate immersive games with avatars, stories and/or characters (e.g. Schroth *et al* 2014), social interaction (e.g. Pérez-Fernández *et al* 2019), and facilitation (e.g. Hoyos *et al* 2019). Meanwhile, role-playing games can be at the same time appreciated and criticized for being games (Bathke *et al* 2019). Games with achievement elements can also lead to engaging experiences, for example those with quizzes and badges (Toriz

2019). In some cases, players explicitly appreciate game challenges (Yamada *et al* 2019), but also consider them too difficult and opaque to be enjoyable (Waddington and Fennewald 2018). Table 15 summarizes all of the behavioral engagement results, including details about the associated interventions, and the game elements reported in the high and medium strength interventions (for more details, see supplementary files S3 and S4).

The results from the sample, and especially from medium and high strength studies, suggest an optimistic future for game-based climate change engagement, especially when studies aim to increase cognitive engagement, affective engagement including motivation to act and interest towards climate change, or in-game social interaction related to climate change. However, heterogeneity in terms of contexts, designs, outcomes and methods hinders drawing global conclusions.

3.5. Quality and strength

This section appraises the studies' quality and ranks their design strength as an indicator of internal validity. These data will help to assess the extent to which the outcomes and results reported above are reliable in their context. Given the broad perspective taken in this review, where multiple interventions for multiple populations are considered, we are not as concerned with the individual studies' external validity or generalizability; it is the overview that provides the wider angle.

3.5.1. Quality appraisal

We assessed the papers' quality through a checklist adapted to the purposes of this review from the examples provided by the Critical Appraisal Skills Programme (n.d.) (see table 16 for details). The score for each of the quality assessment questions (either 0, 0.5, or 1) was assigned independently and then discussed between the two researchers until an agreement was reached for each paper. Overall independent perceptions of quality were similar in all cases and discrepancies were typically at the level of half point.

We classified results in three groups according to our overall judgement after conducting the quality assessment: low quality, when out of 8 possible points the paper scored below 5 (17.2%); medium quality, when it scored between 5 and 6.5 (40.6%); and high quality, when the score was between 7 and 8 (42.2%). In practice, no paper obtained a score under 2. When mapping the quality of the articles versus the years of first publication, we observe a slightly upwards tendency and stabilization in 2017 with the average quality score around 6 (figure 5). The period 2018–2020 has seen more high-quality papers being published than in all the previous years combined, but the number of low-quality papers has also grown.

Table 13. Presence of game elements and affective engagement results in high and medium strength papers.

Game elements	Affective engagement results
<p>Achievements/progression Challenges (16); feedback (14); levels (14); points (10); quizzes (4); increasing difficulty (4); timers (3); leaderboards (3); badges (2).</p> <p>Social Cooperation or collaboration (12); competition (8); peer-rating (2); customization (1); collective voting (1).</p> <p>Immersion Visual game world (12); stories or characters (6); role-play (6); avatar (5); in-game rewards (1).</p> <p>Representation, resources, materials In-game economy (6); debriefing (5); physical playboard (5); physical or digital objects as resources (5); unexpected events (2); randomness (2); real-time dependence (2); facilitators (1).</p>	<p>Individual attitude improvements</p> <ul style="list-style-type: none"> ● Increase in perceived responsibility (multiplayer board game, K-12 students) ● Increased interest in water conservation (single-player digital game, K-12 students) ● Increased appreciation of the environment (role-play, tertiary students) ● Increased intent to engage in discussions and political action (hybrid role-play, K-12 and tertiary students) ● Feeling of empowerment to use new information and skills (hybrid multiplayer game, multiple stakeholders) ● Positive changes in people's attitude towards sustainability sustainable behaviors (multiplayer board game, adults) ● Motivation to research discussed topics (multiplayer hybrid simulation gamifying a course, tertiary students) ● Empowerment, reduced fatalism, motivation to teach others (gamified digital app, tertiary students) ● Confidence about own and other organizations' capacity to adapt (role-play simulations, local stakeholders) ● Activation to learn about climate uncertainty (hybrid simulation game, water managers) ● Increased trustworthiness (multiplayer hybrid game, decision-makers) ● Small rise in self-efficacy (digital and board game played in groups, K-12 students) <p>Concern about climate change and its risks</p> <ul style="list-style-type: none"> ● Increased concern about climate change effects (digital single-player game, K-12 students) ● Concern about local risks (role-play simulations, local stakeholders) ● Concern about local impacts, support for more radical policies, sense of local responsibility (tertiary students, single-player digital game) ● Greater urgency and hope (hybrid role-play, K-12 and tertiary students) <p>Positive observations on collective affect</p> <ul style="list-style-type: none"> ● Optimism about international cooperation, less pessimism on political measures for mitigation (multiplayer board game, K-12 students) ● Slight increase in collective self-efficacy about local energy transition (digital or board game played in groups, K-12 students) ● Increased confidence about collective adaptation action and perceived importance of engaging many points of view in adaptation (role-play simulations, local stakeholders) <p>Empathy for or understanding of others</p> <ul style="list-style-type: none"> ● Increased empathy and recognition of others' perspectives (role-play simulations, local stakeholders) <p>Issues</p> <ul style="list-style-type: none"> ● Fatalism due to game difficulty (single-player computer strategy game, unknown age) ● Decreased trust after engaging in multiplayer competitive dynamics (multiplayer hybrid game, decision-makers) ● Non-significant increase in self-efficacy, limited willingness to save energy (associated with issues with graphics and perceived lack of interactivity in digital games, K-12 students)

Table 14. Presence of game elements and behavioral engagement results in high and medium strength papers.

Game elements	Behavioral engagement results
Achievements/progression Challenges (12); levels (11); feedback (10); points (8); leaderboards (5); increasing difficulty (5); timers (4); badges (3); quizzes (2). Social Cooperation or collaboration (11); competition (10); customization (2); peer-rating (2); collective voting (1). Immersion Visual game world (7); avatar (7); stories or characters (3); role-play (3); in-game rewards (1). Immersion Visual game world (7); avatar (7); stories or characters (3); role-play (3); in-game rewards (1). Representation, resources, materials Debriefing (6); in-game economy (6); physical playboard (4); physical or digital objects as game resources (4); unexpected events (3); facilitators (2); randomness (1); real-time dependence (1).	In-game dialog, cooperation, and competition <ul style="list-style-type: none"> • Dialog, new collaboration opportunities (multiplayer hybrid game, multiple stakeholders) • Discussion in in-game missions (gamified digital app, tertiary students) • Interdependence, social connections developed (multiplayer hybrid game, decision-makers) • Cooperation and competition in a realistic scenario (multiplayer hybrid game, decision-makers) • Coordination among groups in a social simulation (hybrid role-play, K-12 and tertiary students) Personal mitigation behavior <ul style="list-style-type: none"> • Behavior change on sustainability issues (multiplayer board game, adults) • Behavior change after playing (gamified digital app, tertiary students) • Decrease in carbon footprint after participating (role-play, tertiary students) Produced outputs (e.g. games, adaptation plans) <ul style="list-style-type: none"> • Generation of useful content through gameplay (gamified digital app, tertiary students) Personal involvement with study and information <ul style="list-style-type: none"> • Participation and involvement in a university course (multiplayer hybrid simulation gamifying a course, tertiary students) • More study (gamified flipped classroom, tertiary students) Community-level real-world decision-making <ul style="list-style-type: none"> • Integration of in-game projections into local decision-making (role-play simulations, local stakeholders) Issues <ul style="list-style-type: none"> • Increased situation awareness only leads to action if certain conditions exist (e.g. familiarity with climate change actions) (hybrid multiplayer game, decision-makers) • Although some players discussed with friends about the game, few participants engaged in behavior change after playing (single-player computer strategy game, unknown age)

3.5.2. Study design strength

We examined the primary studies' designs in terms of their suitability to evaluate the effectiveness of the intervention on climate change engagement. Studies were classified in three groups according to their design regarding measurement comparisons. In the high strength group, we included only those studies that reported findings on climate change engagement as part of case-controlled studies and experiments (9.4%). The medium strength group consists of before–after studies (31.2%). Finally, the low strength group consists of studies that report qualitative data and studies that measure engagement after the intervention or through quantitative data collected during gameplay but do not have other measures to compare the data with (59.4%).

While more than half of the research outputs were classified as of low strength, the fact that this is an emerging field makes this proportion expected. Considering that a goal of this review is to map the broad field of game-based climate change engagement, we have chosen not to omit those studies, but

to discuss their (mostly qualitative) results according to their relative weight and specific contexts of implementation.

4. Discussion

This study mapped the extant corpus (64 papers) on game-based and gamified interventions on climate change engagement. Its scope included not only interventions specifying climate change engagement as a goal, but also those which sought to analyze currently existing responses to climate change. The inclusive search protocol and the detailed mapping make this study the most comprehensive review of this growing field to date. Our data indicates that game-based climate change engagement is a nascent and growing area of research situated mainly between the environmental and the social sciences. The literature reviewed, all published in the last decade, yields multiple promising results from heterogeneous gamified approaches in diverse situations.

Table 15. Presence of game elements and game experience results in high and medium strength papers.

Game elements	Game experience results
Achievements/progression Challenges (16); feedback (15); levels (14); points (12); quizzes (6); badges (3); increasing difficulty (3); leaderboards (2); timers (2).	Preference and other benefits <ul style="list-style-type: none"> • Appreciation of the game by most players (multiplayer hybrid game, multiple stakeholders) • Preference over other educational methods; appreciation of challenges and learning content, and willingness to recommend (single-player digital games, K-12 students) • Preference over other instruction methods (digital or board game played in groups, primary students) • Preference over other strategies for climate change education (gamified digital app, tertiary students) • Game considered understandable, useful, rigorous, and objective (multiplayer hybrid simulation gamifying a course, tertiary students) • Game considered a safe space for learning, reflection and sharing perspectives (role-play simulations, local stakeholders) • Game considered engaging and informative (single-player digital game, tertiary students)
Social Cooperation or collaboration (9); competition (6); customization (3); peer-rating (2).	Enjoyment, fun, motivation <ul style="list-style-type: none"> • Excitement to play; enjoyment; fun, engagement, interest (single-player digital games, K-12 students) • Motivation and enthusiasm (multiplayer board game, K-12 students) • Fun (digital or analog game, K-12 students) • Enjoyment irrespective of intrinsic motivation towards environmental issues (multiplayer board games, adults) • Entertainment (multiplayer hybrid simulation gamifying a course, tertiary students) • Fun (gamified digital app, tertiary students)
Immersion Visual game world (13); stories or characters (9); avatar (8); role-play (2); in-game rewards (2).	Intense participation <ul style="list-style-type: none"> • More engagement in class (gamified flipped classroom, tertiary students) • High level of attention during the game (hybrid simulation game, water managers)
Representation, resources, material Physical playboard (4); in-game economy (4); debriefing (3); physical or digital objects as game resources (2); unexpected events (2); facilitators (1); real-time dependence (1).	Issues <ul style="list-style-type: none"> • Criticism of games as a method for serious purposes (multiplayer hybrid game, multiple stakeholders) • Issues with graphics quality, lack of challenge, lack of interactivity; bugs; confusion, excessive difficulty, and lack of fun (single-player digital games, K-12 students) • Opaque game mechanics, poor scaffolding of learning (single-player computer strategy game, unknown age)

Table 16. Quality assessment mean scores.

Question	Mean	SD
Q1. Was there a clear statement of the aims of the research?	0.961	0.135
Q2. Was the research design appropriate to address the aims of the research?	0.813	0.289
Q3. Was the recruitment strategy appropriate to the aims of the research?	0.828	0.256
Q4. Was the data collected in a way that addressed the research issue?	0.703	0.342
Q5. Have ethical issues been taken into consideration?	0.477	0.326
Q6. Was the data analysis sufficiently rigorous?	0.602	0.380
Q7. Is there a clear statement of findings?	0.883	0.213
Q8. Does the research provide a valuable contribution?	0.875	0.218
Total score	6.141	1.529

In our review, we found a balance between climate science, mitigation, and adaptation. By including scientific support, that is, a reason for action, policy is more likely to be understood and accepted (Lorenzoni *et al* 2007). Game-based

interventions in the sample also materialize in a variety of formats, from digital to analog to hybrid. In many cases, this indicates a conscious effort to adapt to the players' habits and needs, such as an interest for digital platforms in the case of young

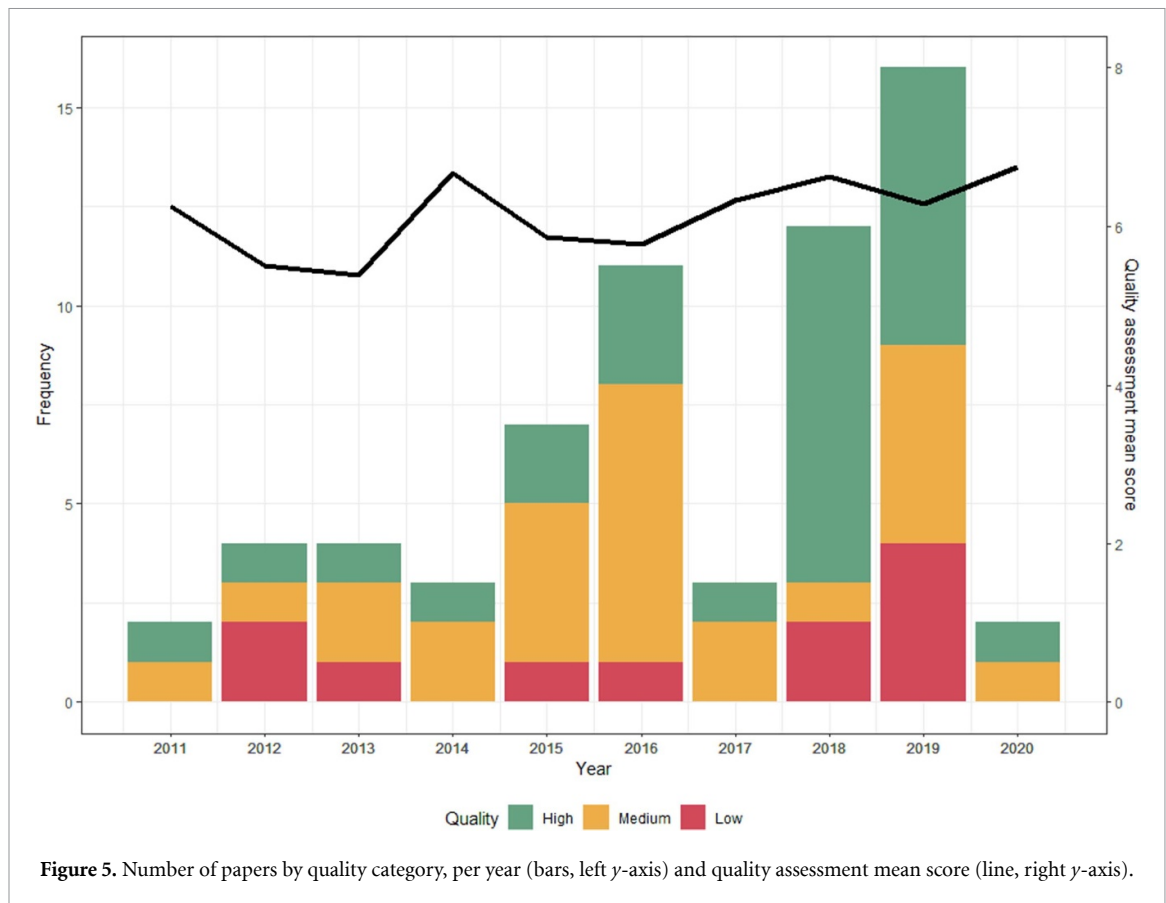


Figure 5. Number of papers by quality category, per year (bars, left y-axis) and quality assessment mean score (line, right y-axis).

students, or the adequacy of software-supported role-plays for professional audiences. In terms of design elements, the games described in the papers go beyond traditional criticisms of gamified solutions, which often present a simplistic design based on points, badges, and leaderboards (Koivisto and Hamari 2019). Here, all games included at least one achievement-oriented element, and over three quarters featured also immersion and social elements.

The vast majority of the results reported indicate that games can impact multiple engagement dimensions at the same time, as well as provide engaging and enjoyable ludic experiences. Thus, although the existence of publication bias or its extent cannot be known or measured, different game-based interventions do seem to result in participants' engagement with climate change. Cognitive engagement appears to be the most researched dimension, including all three application domains (climate science, mitigation knowledge, and adaptation knowledge). Although less numerous, engagement results in all other observed dimensions were reported.

More specifically, as a result of analyzing the papers that used systematic data gathering and data comparison analysis methods, i.e. 40.6% of the sample, multiple examples of effective implementations of game elements for climate change engagement were found. As suggested by

the games and gamification background literature, climate change game-based interventions are often preferred over other methods and can provide motivation, learning through experience, safe spaces for social interaction, and visually supported engagement with complex topics.

However, we also uncovered several areas in which research and design could improve in the future. In terms of context, most contributors work in advanced economies, especially the US and the Netherlands, and conduct interventions there. Advanced economies have some of the highest per capita CO₂ emissions: according to 2016 data, OECD members emitted 9 metric tons per capita versus the 0.3 of the UN least developed countries, and the higher the country income is (not accounting for internal inequalities), the higher the emissions per capita tend to be (World Bank, *n.d.*). This provides an argument for interventions targeting mitigation behavior in those countries. However, developing countries are especially vulnerable to climate change (IPCC 2001), which underlines the importance of adaptation in those areas.

Regarding populations, studies seldom collect data about beliefs, attitudes and values in these areas, or even knowledge about climate change. Interpreting and adequately contextualizing cognitive, affective or behavioral gameplay results becomes difficult without a clear comparison with the players' previous

level of climate change engagement. Moreover, most of the studies in this sample focus on engaging adult participants, many of which are university students, which raises doubts about the possibility of using similar engagement interventions with publics of different educational levels and ages. In addition, players are regularly framed as consumers, professionals or simulated decision-makers, neglecting other possible citizen roles.

Interventions are often short, consisting of only one session and thus limiting their possible learning impact (Wouters *et al* 2013). Despite the breadth of climate change causes, impacts, and possible measures, a few topics concentrate most of the attention, e.g. droughts, floods, economic aspects of mitigation, or climate science. Although games are generally effective in engaging players with climate change, the behaviors measured mainly occur in-game, for example through peer discussion. We also observed problems with game experiences. Players can see games as unfit for professional settings, too difficult or complex, or disconnected from their interests.

Our evaluation reveals a need for more rigorous data collection and analysis methods, better controlled designs and more longitudinal interventions. In this way, results will be more reliable, although comparability will remain a matter of focusing on specific contexts. Finally, we conclude that there is a need for more consideration for ethical issues. From the above findings we propose a research agenda in order to advance this area of study.

4.1. Agenda for future research

In this subsection, we propose a series of recommendations for future research based on the gaps and opportunities detected, divided into the same four parts as our results: contexts and populations; intervention; outcomes and results; and quality and strength.

(a) Population and context

1. **A larger variety of social, political and economic actors can benefit from adequately designed game-based experiences.** Unprecedented climate change mitigation and adaptation measures should be undertaken in practically all areas of society, policy making and economic practice in order to limit global warming (IPCC 2018). This potentially involves wide sectors of the global economy, at multiple scales, and thus permeates multiple areas of human daily life. Over a third of the papers involved populations that were already professionally or educationally involved with the topic. In addition, professional sectors other than farming and water management are virtually unrepresented in this sample, as are local citizens and stakeholders. We believe that a multitude of actors would benefit with a direct engagement with climate

change, be it in terms of how to contribute to its mitigation through political or economic practice, or to adapt to its personal, community, and professional life impacts. Future design frameworks that integrate user-centered design principles applied to gamification (Rajanen and Rajanen 2017) with the specificities of climate change engagement could support such an effort in terms of audience variety.

2. **More information on the participants' background and valuation of games is needed.** Climate change is both a political and an environmental issue, and as such it is important to measure players' leanings in these aspects (Hart and Feldman 2016). None of the papers reviewed identified a significant share of climate contrarianism in the population, with one claiming that the potential players 'who did not participate in the workshops (four out of sixteen farmers) were the only climate-change deniers and remained uninterested' (Sautier *et al* 2017, p 547). Interventions may want to engage further those who do not hold a prejudice against scientific evidence and even show concern for climate change, focusing on the central environmental topic of bridging the value-action gap (Blake 1999). However, they could also motivate participants unconvinced about the rate of climate change and its repercussions, whose current behavior may represent higher than average greenhouse gas emissions, through technological and economic development arguments (Bain *et al* 2012). Irrespective of the target audience, it is important to understand the player's profile to gauge how the effectiveness of solutions varies according to pre-existing conditions. For example, ineffectiveness can be explained by a perceived high level of knowledge (Fjællingsdal and Klöckner 2019) or a current high level of sustainable behavior (Petersen *et al* 2019), as opposed to those with less awareness and concern to begin with (Rumore *et al* 2016). Collecting player perceptions about in-game representations of reality is also important, as extreme skepticism of a game model can seriously hinder learning (Waddington and Fennewald 2018). An understanding of the participants' history with climate change, for example related to experienced impacts that could be attributed to it or perceived relevance in their daily lives, may help interpret their reactions to game-based experiences. In addition, other relevant personal variables such as age, income, aspects of the quotidian environment (e.g. urban or rural, proximity to the coast), and geographical origin should be collected and reported to contextualize findings in themselves and in relation to other literature more precisely.

3. **We encourage researchers from all origins to look more often towards emerging and developing economies.** Climate impacts are expected to be especially dire in developing regions, which rely on agriculture and have more vulnerable populations and more limited economic and technological resources overall (Mertz *et al* 2009). We recommend more game-based interventions to be situated in emerging economies and explicitly linked to locally relevant adaptation measures. In addition, game-based engagement can help raise climate literacy so the relationship between local land use or polluting industrial activity and climate change are understood and sustainable development is embraced. We consider an optimal path involving researchers and institutions from those same countries with native capabilities, who will have, or be able to gather, the cultural and practical knowledge on the challenges and assets within these communities.
 4. **We recognize the need for more research involving K-12 students.** The widely quoted definition of sustainable development as meeting ‘the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development 1987, p 54) directly involves the young of today. More immediately, children are especially vulnerable to climate change and its impacts, and minors around the world declare interest, concern, and even fear of climate change (Clayton 2020). Specific coping strategies for negative affect (e.g. anxiety) can bring, or even consist of, productive engagement (Clayton 2020). Indeed, children and teenagers have gained a more public profile as activists since the climate strikes of 2019. In the reviewed literature, they have even been involved in climate action as facilitators of game-like experiences (Culén *et al* 2016). However, most of the studies in this sample focus on engaging adult participants, the majority of which are university students. As some examples in this review show, game-based engagement directed at young students can favor scientific literacy and even critical engagement with an issue that extends far into their future. Role-plays, campaigns and enquiry-based projects, examples of learning methods recommended for the UNESCO climate action learning objectives (Rieckmann 2017), can be tools to continue this promising line of work and research.
- (b) **Intervention content and design**
5. **Interventions that target specific behaviors, such as energy conservation, should connect explicitly with climate change.** Through the selection process for this review, we have seen that multiple venues publish empirical studies on topics connected to climate change, such as disaster adaptation or energy saving, but they were out of our scope. Although these constitute engagement interventions, their lack of explicit connection with anthropogenic climate change disconnects them from this clear and important reason why, which can lead to failure and rejection at the level of policy (Lorenzoni *et al* 2007). Indeed, knowledge on climate change has been linked to greater concern, which increases perceived efficacy and responsibility to address its challenges (Milfont 2012). It is possible that simplified messages alluding to, for example, benefiting the environment or preventing air pollution, will be a sufficiently meaningful framing in certain contexts. Especially where the implicit connection to climate change is well understood, this will avoid overloading the player with information. In other cases, the disconnect between individual or community behavior and the global changes that they aim to address can be a lost opportunity to create broader knowledge, a deeper sense of importance and purpose, and motivate behavior beyond short campaigns and extrinsic rewards. Thus, connecting localized issues with the big picture is a strategic decision to confront.
 6. **In-game actions could have real-world impacts by design.** If the changes needed to mitigate and adapt to climate change affect all areas of life, citizens can adopt multiple roles as economic, political and social actors. However, environmental action is complex and demanding. Multiple variables relate to the truly environmentally responsible citizen, including ‘information, awareness, concern, attitudes/beliefs, education and training, knowledge, skills, literacy and responsible behaviour’ (Hawthorne and Alabaster 1999, p 26). Furthermore, multiple barriers stand in the way between citizens, environmentally protective behavior (Pelletier *et al* 1999), and climate action specifically (Gifford 2011, Whitmarsh 2011). Gamification could have a prominent role in connecting game-based engagement with direct real-world behavior. As shown by various interventions, players can solve game challenges through real-world action (e.g. Lee *et al* 2013). These need not be limited to consumption, but could embrace the spectrum of possible public roles, from supporter to participant in science and policy discussion (Wibeck 2014). More game-based research could afford direct participation in real fora by promoting social discussion and collective action,

either through official, non-governmental, or informal channels.

7. **Extended exposure to games and combination with other methods can multiply the learning impact of game-based interventions.** Serious games are more effective in driving cognitive learning results when they span multiple sessions and/or are combined with other instructional methods (Wouters *et al* 2013). Given that most interventions were delivered in a single session, limiting the engagement time of players to a few hours at best, this longitudinal dimension should be explored further in the future, especially considering that a crucial goal of engagement interventions is promoting the understanding of a complex phenomenon comprising climate change causes, impacts, and possible actions. In the area of climate change adaptation, long games 'are more likely to create deeper player engagement that challenges existing mental models, changes player behaviour, and catalyses action by enabling players to make climate change adaptation decisions in the face of uncertainty' (Flood *et al* 2018, p 18).
8. **Games can explore the breadth of existing and potential climate impacts beyond the most known.** Many research outputs simulated the occurrence of climate impacts through, for example, randomization or unexpected events, mimicking uncertainty as a key component of the otherwise complex and ill-defined climate change issues (Rebich and Gautier 2005). However, few studies focus on specific impacts of climate change beyond those related to high temperatures and lack of precipitation (drought, desertification, increasing temperatures, and heatwaves) and floods. The impacts of sea level rise, extreme weather events, ocean acidification, disease spread, conflicts for natural resources, human displacement or ecosystem threats, to mention a few, are underrepresented. Other climate science concepts, such as tipping points, have not been referred to at all. Especially for interventions that are situated in real communities, detecting the existing or potential climate-related threats can be of utmost importance to generate a sense of connectedness to the situation on the ground. As an example, reframing climate change as a health issue has been found to make it more relevant and understandable (Maibach *et al* 2010). Thus, we recommend detecting previously unexplored frames and identifying those symbols (stories, synecdoches, and metaphors, as exemplified in Onenkan and Van de Walle 2018) that will resonate with particular audiences and make familiar the intangible problem of climate change.

(c) Engagement results

9. **Behavioral engagement outcomes need to be measured more carefully.** Overall, the most reported engagement results were cognitive in nature, either behaviorally assessed (for example, through a test-like questionnaire) or psychologically inferred (usually self-reported or observed by a researcher). Behavioral engagement was, for the most part, in-game social interaction, as few studies reported real-world impacts during or after the intervention. Similar shortcomings in evaluating long-term and/or behavioral engagement were observed also in other reviews focused on interventions targeting more localized issues. For example, in a review of 26 articles on game-based interventions for domestic energy consumption, only ten measured real-world behavior, nine of which had a positive impact (Johnson *et al* 2017). As explained in point number 6, above, the necessary changes in real-world direct behavior could be implemented in the game design process itself. Nevertheless, they could also be encouraged and measured as a consequence of engaging with a completely fictional game experience.
10. **Data collection should be extended in time.** Related to the previous point, and to point 7, above, on longitudinal exposure to the games, it is important to understand how profound and lasting changes are, in all three climate change engagement areas, and to assess game-based interventions' effectiveness more holistically. In this review, a dearth of longitudinal research has been observed, with only five research outputs that followed up the participants. Furthermore, these studies included a form of delayed post-intervention data collection and varied in terms of topics, designs, sample sizes, and elapsed time after the intervention, complicating any possible meaningful comparison. Although resource-consuming, following participants systematically weeks and months after the interventions, especially if these yielded significantly positive results, would help understand the potential and actual magnitude of the effects. Prospective cohort studies comparing individuals with different degrees of exposure to climate change gamification interventions would also provide a deeper understanding of games' impacts.

(d) Quality and strength

11. **Rigorous research methods are needed to draw more reliable conclusions.** Our quality assessment suggests that studies sometimes fail to employ an appropriate data collection

method or analyze data rigorously. Some papers lack clear reporting of critical aspects such as sample size and selection, and measurement instruments. While knowledge questions are not always the best learning assessment tools (Chin *et al* 2009), using them in addition to the already common self-reported outcomes could give a more comprehensive picture of cognitive engagement. Moments of data collection are also important, with more pre- and post-intervention measurement designs encouraged. In cases in which a group discussion is part of the program, researchers should consciously determine when to collect individual feedback: doing so between the game proper and the debriefing would lead to an ‘uncontaminated’ account (Chin *et al* 2009) but would not take into account the socially constructed reflective knowledge resulting from discussion. In addition to identifying the roles and suitable measurements of the psychological impacts of the game experience on climate change engagement, physiological and objective behavioral measures such as eye tracking should be also defined and employed as they may be effective methods for studying and capturing engagement (Wouters *et al* 2013), although they have not been used at all in this sample. Finally, methodological soundness would benefit from explicit ethical considerations, which are often missing.

12. **More controlled designs with rigorous conditions are needed.** Some papers show strong research designs and/or high-quality reporting, thus providing examples of the kind of research that is needed. However, more experimental studies with large samples and rigorous inferential analysis methods would help assess the effectiveness of game-based climate change engagement more precisely and reliably. Even when including control groups, too often studies lack control conditions with informational content comparable to that in the games (Soekarjo and van Oostendorp 2015). If the goal is comparing games to other media, or even games in different media (e.g. Erb 2015), ensuring that this is the only variable that changes between groups, while preserving the same content material and method of instruction, is a major challenge (Clark 2001). Furthermore, even if games give a better result than a different medium, effect sizes should be considered to justify a potential game choice over an alternative that is easier to implement. For example, research on instructional effectiveness focuses on effect sizes of at least $d = 0.4$ (Mayer 2019). In addition to media comparison studies, we encourage research that helps understand the effects of isolated game features on climate

change engagement. As mentioned in the results, value-added game research could be a useful method (Mayer 2019). Other approaches that would increase the strength of studies without requiring a direct manipulation of the games include controlling for player variables such as age, experiences of climate change, professional background, game preferences, or intrinsic motivation towards the environment (e.g. Gugerell *et al* 2018), or examining how players’ in-game actions may correlate to engagement outcomes (Meya and Eisenack 2018). Finally, manipulation checks in experiments would help researchers determine if the game treatment is representative of the independent variable that is theorized as causing the change in climate change engagement. In this way, studies could measure both convergent validity (the intervention is perceived as intended, from general game experience indicators such as the game being enjoyable, engaging, flow-inducing, or intrinsically motivating, to particular elements such as a character being relatable) and discriminant validity (no unexpected effects result from it, e.g. an added story unintentionally reiterating content) (Highhouse 2009).

5. Conclusion

In this article, we systematically reviewed 64 research outputs that engage players with diverse climate change issues through game-based interventions. In particular, we examined populations and contexts, formal features, outcomes, and the study designs and analysis methods employed. We found that this area of research has been growing for the last decade, both in overall quantity and in number of high-quality papers. Interventions engage various populations with scientific topics, mitigation, and adaptation across the climate change engagement dimensions, while providing generally well-received game experiences. A variety of formats are used depending on the context, usually using design features that promote achievement, immersion, and social interaction.

Nevertheless, we found diverse areas in which both research and design practices could improve in the future. Based on these gaps, we articulate 12 recommendations in a research agenda that researchers and practitioners should consider in the future in order to explore the full potential of gamification for climate change engagement. These recommendations have implications in the four areas of our analysis: who do these interventions target and in what contexts, their design, their engagement results, and their strength and quality. First, in terms of contexts and populations, we propose to situate interventions in emerging and developing economies, to understand better the participants’ background regarding

climate change and games, and to extend the targets to young students and more social, political and economic actors. Second, interventions themselves should strategically position their content within the larger frame of climate change, design actions so they have a real-world impact, extend beyond single sessions, and tackle understudied climate manifestations. Third, to complement existing results, behavioral outcomes should be more sought, and data collection extended in time. Fourth, to increase research quality, we propose more rigorous research methods and designs.

The authors of this review acknowledge its possible limitations. Apart from the involuntary errors that could occur in coding a complex landscape such as this one, the heterogeneity of the studies in terms of populations, contexts, and intervention types has led us to offer a broad overview here. Future reviews will be able to answer more specific questions. We also provide an overview of multiple engagement dimensions, which limits the level of detail provided in reporting each one of them. Future reviews can focus, for example, exclusively on cognitive engagement outcomes, detailing different concepts articulating climate change cognitions. The conducted quality and strength analyses are focused on identifying gaps in literature to further provide recommendations for future research. A meta-analysis focusing on the relations between quality and strength and specific variables, such as the background of the participants in relation to climate change, or the engagement results of the literature, is suggested as future work. Methodologically, we rely on multiple relevant databases and complement our process with a forward snowballing search, but we did not include a backward search due to its large resource requirements and possibility of small or naught return. However, our methods allow us to assume that we reviewed an exhaustive sample of the empirical game-based climate change engagement in the last decade.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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