International Journal of Child-Computer Interaction 38 (2023) 100605

Contents lists available at ScienceDirect

International Journal of Child-Computer Interaction

journal homepage: www.elsevier.com/locate/ijcci

Review article

The role of CCI in supporting children's engagement with environmental sustainability at a time of climate crisis

Asimina Vasalou *, Andrea Gauthier

UCL Knowledge Lab, IOE, UCL's Faculty of Education and Society, United Kingdom

ARTICLE INFO

Keywords:
Environmental sustainability
Technology
Design
Children

ABSTRACT

Today's children will live life navigating the impacts of climate change triggering new questions about their environmental education and how we can prepare them to take active roles that shape our ecological futures. The aim of our paper is to reflect on the role that the Child–Computer Interaction (CCI) community can play to this end. We do this by analysing thirteen years of HCI research concerned with the application of children's digital technology to environmental sustainability (ES). Content analysis of the 25 papers identified shows that climate change is not a motor theme, with half of the papers using ES as an application area that drives other aims. Our analysis contributes a novel research agenda proposing to expand the domains, theories and user groups researchers have thus far focused on. Examining the distinctive design properties of previous research, we advance new insights into the role technology can play for children's ES.

1. Introduction

Children are growing at a time when the impacts of climate change are part of life as we know it. One report by UNICEF (UNICEF, 2021), estimated that approximately 1 billion children, i.e., half of the population of children globally, are at extremely high risk to climate and environmental hazards, shocks, and stresses and those living in the Global South are the most vulnerable. Since the first global policy efforts to curb global emissions began (Klein, 2015), it has become clear that the timeframe for mitigating the effects of human action on the climate is indeterminant, and children will play an important role in shaping the security and equality of our ecological futures. Recognising children's role and future responsibility, however, triggers new questions on how educators, parents, and communities can support them in developing ecological identities, as well as the knowledge and skills to react to these challenges. Thus, policy makers, activists, researchers, and education communities among others have been engaged in an active project to redraft what children's environmental education might look like (Dunlop, Rushton, Atkinson, Ayre, Bullivant, Essex, et al., 2022 and Perkins, 2018). In one such illustrative example, one research project led on a collaborative manifesto-making for education involving 200 children and their teachers in the co-creation of a value-driven vision of environmental education with sustainable action at its centre (Dunlop et al., 2022). While recognising the multidimensional and thus multi-stakeholder involvement required in shaping this new learning, the inevitability of children's interface with climate change impacts over their lifetime underscores the importance of involving them in these developments, and thus the need to be led by children's voices has been raised as a critical sensibility (UNICEF, 2021).

Harnessing digital technology to improve contemporary challenges in children's lives is not new to HCI researchers concerned with child–computer interaction (CCI) who have grappled with topics ranging from children's obesity and physical health (Høiseth & Van Mechelen, 2017) to the inclusion of disabled children in social life and education (Benton & Johnson, 2015; Vasalou, Ibrahim, Clarke, & Griffiths, 2021). The same research community has had a long history of developing novel methodological approaches for involving children in the process of digital technology design whilst taking a critical stance of top-down design approaches led by adult stakeholders (e.g., Benton & Johnson, 2015 and Druin, 2002). CCI researchers are thus well poised to take a leading role in shaping children's digital technologies for Environmental Sustainability, hereon referred to as ES. However, even though several substantive reviews on "Sustainable HCI" have been published (e.g., Bremer, Knowles, & Friday, 2022; Knowles, Bates, & Håkansson, 2018 and Scuri, Ferreira, Nunes, Nisi, & Mulligan, 2022), there has been no effort to consolidate how CCI research has engaged with this topic through its child-centred lens. In this paper, we aim to examine (i) the publication trends and genres of CCI research concerned with ES, (ii) the

* Corresponding author.
E-mail addresses: a.vasalou@ucl.ac.uk (A. Vasalou), andrea.gauthier@ucl.ac.uk (A. Gauthier).

https://doi.org/10.1016/j.ijcci.2023.100605
Received 18 January 2023; Received in revised form 7 July 2023; Accepted 19 July 2023
Available online 27 July 2023

beneficiaries of this research and (iii) how digital technology has been designed for children's engagement with ES.

To achieve these aims, we identified research papers concerned with children's technology and ES over a fourteen-year period. The papers were identified from two CCI flagship venues (Interaction Design and Children 'IDC' conference, International Journal of Child–Computer Interaction 'IJCCI') in addition to the CHI conference reflecting the origins of the IDC research community (Read & Bekker, 2011). Additionally, a broader search in Scopus and the ACM library was carried out to identify papers expressing their contribution to CCI. Through structured content analysis, we probe specific dimensions of this past research, such as the types of research conducted, the ES domains covered, and theoretical as well as design sensibilities underpinning past digital technology design. Our paper makes three main contributions: first, in a striking contrast with the urgency of the climate crisis, we find that ES has not been a central theme within the CCI venues explored with only 31 papers published overall, half of which treated ES as an application domain rather than a central domain of inquiry; second, our analysis of the available papers consolidates current understanding of how CCI has used the distinctive properties of various technologies to advance children's engagement with ES. We summarise four design themes emerging from this analysis – '*making the hidden visible mobilises action*', '*supporting the exploration of cause–effect relations*', '*making as a way of expressing and negotiating ES*' and '*creating attachments and affective connections*' – to contribute a first outlook on how digital technology can benefit children's ES. Finally, by exploring the patterns of current CCI research, we develop a 'Call to Action' comprising five opportunity areas that invite CCI researchers to extend ES research into critical, and yet currently underrepresented, directions.

2. Background

2.1. How systematic reviews inform CCI

Over the past decade, several systematic reviews have been carried out to describe and inform the field of CCI. By characterising the body of research to date, this work has been able to detect core mobilising topics, identify emerging areas for research that warrant attention, and raise new research implications for the community e.g., Giannakos, Papamitsiou, Markopoulos, Read, & Pablo Hourcade, 2020; McDermott, Robson, Winters, and Malmberg (2022) and Yarosh, Radu, Hunter, and Rosenbaum (2011). To our current interest, ES has not been identified as a core, emerging, or declining topic in these analyses (Giannakos et al., 2020; McDermott et al., 2022), suggesting that this area is either not particularly active or coherent in how it is represented through relevant keywords by authors.

In seeking to understand how ES may fit within CCI research, it is useful to consider the trajectory and focus of CCI research more broadly. Using co-word analysis to identify prevalent CCI topics, Giannakos et al. (2020) showed that CCI interests have shifted over a period of 15 years with constructionism and programming being supplanted by games, robot–child interaction, or storytelling, for example. Giannakos and colleagues also found a consistent use of ancillary topics in CCI papers such as "design methods", "participatory design", "learning", and "education" used by authors to introduce the broader scope of their work, which was corroborated by McDermott et al.'s (2022) topic modelling analysis of CCI research over a 17-year period. It is this very expertise that we argued earlier that places CCI researchers in an opportune position to design digital experiences that stimulate children's engagement with ES.

Several reviews have indicated that CCI has tended to generate artefact-focused papers (Giannakos et al., 2020; Yarosh et al., 2011) motivated from a technology perspective. Speaking to this concern, McDermott et al. (2022) found an increasing trend toward keywords related to user groups (e.g., pre-school children), which they interpreted to indicate a shift toward what they termed a needs-focused agenda. However, the same authors also detected that CCI has evolved in pace with contemporary technological developments, which can be seen in the keywords generated by Giannakos et al. (2020) in their CCI analysis reported above. The balance between designing for technological innovation and maintaining a critical approach to a societal/education need, thus, continues to remain a challenge in CCI research. From the prism of ES, we caution that research driven by technical aims will have little impact on children's evolving ES engagement or learning, and thus needs-focused research is critical (see also Bremer et al. (2022)).

Alongside these general reviews of the CCI field, systematic reviews have pivoted the understanding of specific challenge areas. Focusing on the rise in global child obesity, Høiseth and Van Mechelen (2017) reviewed 14 years of research in CCI finding that only 3.4% of the papers published in the Interaction Design and Children conference were concerned with this topic, with the majority of papers addressed to children between 7–15 years old. Noting the incongruence between the scale of the problem and the share of papers published, the authors also identified a dominant perspective on preventing obesity predominantly through games that engage children in physical exercise. Moreover, looking into the theoretical lenses reported in their corpus, the authors found that only a third of the papers reviewed mobilised theory to inform the research, an issue highlighted by Yarosh et al. (2011) in their general review of CCI seven years earlier. Importantly this analysis raised the need for a more diverse technology landscape that draws upon multidimensional perspectives, including nutrition and wellbeing, to also address the occurrence of childhood obesity. In another systematic review, of adolescents' online safety, Pinter, Wisniewski, Xu, Rosson, and Caroll (2017) were able to raise similar critical points observing that the papers within their corpus equated children's exposure to risk with harm. Thus, much of the available research they surveyed aimed to limit risk exposure neglecting to recognise that children must learn how to negotiate risks. These selective examples of prior work clearly show that reviews of contemporary challenge areas, which climate change and ES are, can generate new insights that have the potential to steer the direction of future research. They also indicate specific analytic foci, e.g., populations of children CCI researchers have focused on, alongside the theories, perspectives, and technologies they have employed, that inform the present work.

2.2. From environmental sustainability to sustainable HCI for children

Sustainability is regularly characterised as pertaining to three pillars — society, the economy, and the environment (Purvis, 2019). It is argued that persistent prioritisation of one pillar leads to weaknesses in the other two. We have observed this in real time over the past century, wherein our economic growth has been prioritised over the natural environment, e.g., through the exploitation of fossil fuels and other resources, which has resulted in environmental degradation and climate crisis, often with subsequent social implications, e.g., homelessness due to natural disasters, famine due to severe drought, illness due to contaminated water and air (Pörtner et al., 2022). Whilst those in the Global South disproportionally suffer the ill effects of climate change, the Global North is not left unscathed, with recent increases in wildfires, droughts, and floods impacting those in arid and coastal regions (Pörtner et al., 2022). As such, there is a recognised necessity for governments and publics across the globe to shift their attention toward supporting the environmental and social pillars of sustainability. At policy level, this is reflected in the United Nations' Sustainable Development Goals (SDGs), set out in 2015, which cover a range of environmentally (e.g., SDG13 climate action, SGD14 life below water, SDG15 life on land) and socially (e.g., SDG3 good health & wellbeing, SDG4 good quality education, SDG16 peace, justice, and strong institutions) oriented goals, as well as goals that bridge social/environmental and economic factors (e.g., SDG7 clean and affordable energy, SDG11 sustainable cities and communities, SDG12 responsible consumption & production) to achieve a world that is sustainable in the long-term.

Before we provide a definition of ES, we recognise that ES has been theorised through different disciplinary lenses each with its own epistemological underpinnings. Goodland (1995) defines ES as the "maintenance of natural capital" in a way that "seeks to sustain global life-support systems indefinitely", which highlights the common mindset of the environment as an asset through which to maintain human economy and society. Goodland acknowledges this anthropocentrism and reflects that this definition does not give enough appreciation for the importance (or rights) of nonhuman species outside the context of how they benefit the economy. This has been addressed in more recent definitions, such as work by Nxumalo, Nayak, and Tuck (2022) who highlight "the colonial and racial capitalist relations that drive the climate crisis" affecting human/non-human lives or Morelli (2011), who emphasises that humanity is only a part of a complex ecosystem, redefining ES as "the condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity". Not only does this latter definition frame the systemic nature of ES and humans' role in it, but it also alludes to the multi-domain nature of it.

The "needs" that human society demands from the environment are diverse and touch every aspect of our lives, including transportation, energy use, food production, waste management, architecture and infrastructure, various fabrication industries (e.g., electronics, clothing), amongst others, and all of which can have diverse negative environmental impacts, such as polluted air, ground, and water sources, habitat loss, and reduction in biodiversity (Hawken, 2017). As such, interdisciplinary knowledge and skills will be required to reduce our impact, reverse the climate crisis, begin to reconnect with nature and find balance. As an interdisciplinary field, HCI research concerned with sustainability, i.e., SHCI, has aimed to (i) "limit environmental consequences related to computing technology", i.e., sustainable design, and (ii) "use computing to help effect pro-environmental behaviours" (Bremer et al., 2022). Our work situates this latter aim within CCI. Since today's children and teens will form the workforce tasked with tackling these issues, we argue that technology will play a vital role in stimulating their knowledge, interests, and skills to enable them to achieve this. Alongside using computing to impact children's conscious pro-environmental decisions into the future, we also recognise that technology is a material artefact that could be used to introduce children to sustainable design, e.g., informed by lenses on cradle-to-cradle design, circular economy, or upcycling (Desing, Braun, & Hischier, 2021; Schischke, Proske, Nissen, & Schneider-Ramelow, 2019).

In asking which other disciplines could participate in an *Environmentally Sustainable* CCI research agenda, several existing theories and frameworks are already well positioned to inform the design of technologies that foster children's engagements with ES. We provide selective examples to illustrate this. *Environmental psychology* has focused on how children develop connections to and stewardship of the Earth. For example, Lehtonen, Salonen, Cantell, and Riuttanen (2018)'s pedagogy of interconnectedness postulates that we can help people find their 'place' in nature through embodied and experiential learning that positions the learner as part of the ecosystem, helping them become aware that the wellbeing and needs of humans is on par with the wellbeing and needs of the natural world. Monroe, Andrews, and Biedenweg (2008) defined a framework for *environmental education* strategies, wherein interventions (technological or otherwise) can promote learning about ES through conveying information, building understanding, improving skills, and/or enabling sustainable actions. The framework's focus on enabling sustainable actions has been also raised by those in the field of SHCI who have suggested that digital interventions should be designed to enable real-time change in situ (Knowles et al., 2018). Looking within the field of SHCI, one focus has been to support sustainable action through theories on *environmental behaviour* and *eco-feedback*, e.g., from environmental monitoring, to show a user how their behaviours are impacting the world around them, *eco-spurring*, to incentivise desired behaviours and penalise undesired behaviours, and *eco-steering*, to facilitate the desired behaviours through designed constraints in the technology (Bhamra, Lilley, & Tang, 2011). Other work in the *visual arts* has also drawn on theories of behaviour change to model ways of living and nudge conventional knowledge in a more sustainable direction (Lineberry & Wiek, 2016), as well as inspire visions of a sustainable future (Knowles et al., 2018).

To summarise, our paper seeks to understand how CCI has engaged with ES. Our work is motivated by the global impact and scale of climate change and relevant education developments, as well as policies to revitalise children's education to include an ES focus. To our knowledge, this is the first attempt at systematically analysing CCI's research in this domain which we argue is urgently needed to steer research in this important challenge area. We apply a descriptive literature review seeking to answer the following research questions (RQs). Aiming to describe the publication trends and types of CCI research concerned with ES, we asked: *What are the publication trends and research genres of CCI research as it applies to ES? (RQ1)*. Aiming to explore the beneficiaries of CCI research to date and how digital technology has been designed to engage children with ES, we asked: *Which user groups and contexts has CCI prioritised in its research? (RQ2), How has ES informed CCI research? (RQ3), and What types of technologies have been used (RQ4a) and how has technology been designed to foster children's ES? (RQ4b).*

3. Methodology

3.1. Literature review and sampling strategy

We applied a descriptive literature review (Paré, Trudel, Jaana, & Kitsiou, 2015) which involves the systematic analysis of individual papers to identify research trends (e.g., in relation to author activity, theories, methodologies, findings) within a focused area of research, in our case ES. Driven by our RQs, as part of the descriptive review approach, we carried out a quantitative and qualitative analysis with respect to the size and content of CCI papers applied to ES. By CCI we refer to research intersecting with HCI, concerned with interaction design and children (Read & Bekker, 2011). To capture the dominant HCI perspectives on children's technologies and ES, our sampling strategy initially drew papers from three flagship publication venues that have been also the basis of previous CCI reviews (reported in Section 2.1), either seeking to describe CCI as a field or to understand trends in key challenge areas. These were: (i) ACM's 'IDC' Conference Interaction Design and Children, which is the leading conference for CCI researchers and has been running since 2003; (ii) the 'IJCCI' International Journal of Child–computer Interaction, initiated by the IDC community in 2015; and (iii) ACM's 'CHI' Conference on Human Factors in Computing, which has a dedicated "Learning, Education and Families" track reflecting a CCI focus. To expand the size of this corpus, we carried out a broader search which we report under 3.2.

3.2. Search method

Our search period focused on a span of fourteen years between 2009 and 2023. We chose to start the review in 2009 due to the introduction of the United Nations' Millennium development goals (precursors to the SDGs) in December 2008, which raised global recognition on sustainability and climate change and provided a framework for change.

In deciding upon our search keywords, we wanted our search to identify papers that reflected the diversity of relevant domains. We were also cautious to avoid the inclusion of papers that focused on related topics without concern for humans' impact on, or relationship to the nature/environment, e.g., the conservation of natural ecosystems, perpetuation of the climate crisis. For example, one paper we considered, but excluded, was on wildfires. The data modelling technology discussed in the paper was designed to foster children's scientific understanding of wildfires, yet the link to climate change was not made (Wagh et al., 2022). CCIs interest in digital nature interventions was established in a recent HCI systematic review (Webber, Kelly, Wadley, & Smith, 2023). Thus, not surprisingly, we also considered, but excluded, several papers whose aim was to foster child play or interactions with nature but without making a direct connection to ES e.g., children's role in conservation, stewardship, or the human impact on nature.

In recognising that ES has not been picked in previous topic/keyword analyses' of CCI research (Giannakos et al., 2020), we chose to take an iterative approach to identify our keywords initially focusing on IDC research papers. Papers were selected based on their title and abstract following Eriksson, Gökçe, and Torgersson (2022) and Høiseth and Van Mechelen (2017). The first author accessed and read the paper titles/abstracts from the yearly IDC conference proceedings. The following keywords informed an initial top-down reading: "sustainability", "climate change", "global warming", "environment", "ecology", "ecosystem". At the same time, a bottom-up approach was taken which led to identifying new keywords: "nature", "stewardship", "conservation", "biodiversity", "recycling", "upcycling", "waste", "energy", "ocean", "deforestation". In a second step, both sets of search terms were used to identify papers from the remaining two venues: IJCCI (through Elsevier's interface) and CHI (via the ACM library). In the case of CHI, we added the keywords "child*", "teen*", "young people" to filter papers concerned with these user groups. The titles and abstracts of the resulting search items were scanned for possible inclusion, which was followed by a full-text review to select papers that met our aim. Following a close reading of the papers identified to exclude red herrings, 28 papers were retained: 20 from IDC, 7 from IJCCI and 1 from CHI.

To expand the paper corpus, we carried out a broader search in Scopus and the ACM library to identify papers addressing their contributions to the CCI discipline. We used the same set of sustainability-related keywords generated in step one adding one new keyword: 'child-computer interaction'. This ensured that papers in other publication venues, yet addressing their contribution to the CCI field, were not excluded. The titles and abstracts of 496 items were screened for inclusion by the two authors in a fully crossed design (Cohen's Kappa = 0.93). Based on the initial coding, 33 *new* items were considered for inclusion (the search also produced 10 papers that were already in our dataset). A full-text review of these items was then conducted to check that the papers referred explicitly to CCI and met our criteria. For most, "child-computer interaction" only appeared as journal titles in their reference list, thus resulting in their exclusion. After a full-text review of these new items, 3 were included in our final dataset (all published in OzCHI), bringing the grand total to 31. The paper corpus can be found in the Appendix at the end of this paper.

3.3. Codebook and analysis

Our first aim was to describe the extent of CCI research activity in relation to ES, which was carried out deductively (reported in 3.3.1). Our second aim was to describe the type of research carried out in relation to ES and its conceptual underpinnings (reported in 3.3.2, 3.3.3, 3.3.4, 3.3.5). In the following sections we explain the deductive and inductive approach we used. While the codes used were directed by the RQs, except for categorical codes, subcodes were inductively derived and generated from the content of the papers mirroring the approach taken in past work (Høiseth & Van Mechelen, 2017). The analysis was underpinned by an interpretive lens and was undertaken by the first author. To ensure rigour, and manage subjectivity, the two authors met to discuss the codes. This collaborative approach to coding allowed us to regularly specify the criteria guiding the application of the codes across the corpus and discuss ambiguous cases.

3.3.1. Publication trends

We analysed the distribution of yearly **papers** in our corpus to gauge publication levels over time allowing us to understand if publication outputs within the community have increased over time. While this analysis is revealing of the publishing activity within our dataset, in wanting to understand the size of the community involved in this activity, we also calculated the total number of collaborating **authors**. In addition to the total number of authors, we wanted to gauge if there was research leadership in CCI's research programme. We thus calculated the number of **repeat authors** within the papers included in our corpus. Finally, we coded authors' self-referencing. This allowed us to detect if the included paper was part of a mature research programme, with ES at its heart. We carried out **backward and forward snowball referencing**. Backward snowball sampling refers to self-citations of the authors' previous research (Wohlin, 2014). We compared the author names to the focal paper's reference list and counted all unique self-references. Thus, if two authors had published a single output together in the past, we counted 1. Forward snowball sampling refers to finding new papers published by the same authors citing the paper in the corpus (Wohlin, 2014). We accessed the Google Scholar's citation metric for each paper and compared Google's reference list to the author list. To mitigate against the possibility that self-references were not relevant to the ES focus, we read each referenced paper's title and abstract using the same technique for initially identifying the paper corpus. This revealed that many authors were citing research underpinned by different goals (e.g., a broader methodological approach, considerations for a technological innovation). In those cases, we judged that the cited papers were not contributing to the deepening of ES research, and we did not count them. To capture this practice, however, we coded these instances in two new separate codes, one for back and the other for forward snowball referencing.

3.3.2. Research genres

In their review on values, Yarosh et al. (2011) proposed three research types: "contributes a study", "contributes a system", "contributes a reflection". When applying these codes to our paper corpus, however, we were not able to capture the granularity of the research types we observed leading us to develop five, new codes: a "concept" paper articulates a critique/re-framing of a research area without the analysis of empirical data, "empirical study" carries out research to generate new understanding and insight about users/technology/methods, "design-oriented research" seeks to produce new knowledge through design activities and methods, "prototype evaluation" evaluates a new bespoke prototype with users, and finally, "learning through the process of design or making" refers to papers that report on children making their own technology. When papers crossed genres, more than one code was applied which was the case for three papers (Dobal & Lalioti, 2021; Mylonas, Amaxilatis, Pocero, Markelis, Hofstaetter, & Koulouris, 2019; Underwood, Smith, Rubegni, & Finney, 2022) which combined a "prototype evaluation" with "learning through the process of design or making".

3.3.3. Target users and context

In alignment with past work (Høiseth & Van Mechelen, 2017; Yarosh et al., 2011) we identified characteristics of the end users involved in the research and their contexts, namely by examining the abstract, introduction and the methodological sections of each paper where this focal information appeared. We coded for the **geographical region** in which the research took place, the type of **user group** the technology was designed for/evaluated with (including adult stakeholders, e.g., teachers), the child's **age**, and the **context** of use for which the technology was intended. For the user group code, specifically, we inspected the design narrative, the methodology, and findings to identify whether adult stakeholders were meaningfully included as participants. This code was not used if a paper mentioned the inclusion of teachers for behaviour management or supporting the orchestration of a child-centred study. All sub-codes were iteratively refined based on the information available in the papers. In the case of children's age, all the papers addressed a wide age bracket and thus this sub-code reflected this. We note that a small minority of papers referred to education stages or grades (e.g., Middle school) and for those papers we inferred the ages. Finally, given the recognition that certain communities and geographical places experience climate change impacts more profoundly (UNICEF, 2021), we included a categorical code to capture whether the sampling reported in the papers was positioned as targeting a **group of children at risk** of climate impacts.

3.3.4. Conceptual underpinnings

This category was concerned with the role ES played in the research and how it was conceptualised. Three codes were developed to deepen our understanding of this. As described in the Background, a recent analysis of the CCI field found propensity for tech-driven research (McDermott et al., 2022). This informed the inclusion of a categorical code to assess whether ES was the primary **research motivation** of the paper. Motivation was ascertained by: (i) assessing the introduction to determine if the research was framed against an ES concern or need; (ii) inspecting if the research questions reflected an ES focus, and (iii) evaluating whether the discussion drew relevant implications for the use of digital technology in ES. Here we note that while all papers considered a digital technology designed for ES, their research motivations did not always speak back to ES. We coded also if the paper included ES **theory** to motivate the technology design and/or research approach. This was carried out through an inspection of the theoretical background section and reference list. Since the scope of ES is wide reaching and taps into all aspects of life from food to energy, or urban living, similar to review papers in the broader space of Sustainable HCI (Bremer et al., 2022; Knowles et al., 2018), we coded the **domains** CCI researchers reported in their papers to examine the focus of this research activity.

3.3.5. Technology type

The final category was concerned with the technology itself and the role it played in engaging children with ES. We took different strategies to code this theme depending on the paper's research genre. Papers reporting "a prototype evaluation" always included a section with a detailed design rationale, which formed the focus of our analysis. In contrast, for the remaining genres, a holistic reading of the paper was carried out to identify the sections where the focal technology researchers aimed to inform was described. A code was set up to identify the **technology type** discussed in the paper, with relevant sub-codes generated bottom-up (also Høiseth and Van Mechelen (2017)). Where a paper combined more than one technology type multiple sub-codes were applied.

Next, we coded how the papers articulated the **role of technology,** i.e., by describing how the digital technology affordances contributed to ES and children's engagement. In contrast to the content analysis approach taken across the rest of the coding, an inductive thematic analysis was carried out to identify latent design themes across the papers. Focusing on the technology description presented in each paper, the first author took notes on how the paper justified its design features. Based on these mini descriptions, the same author inductively identified patterns that described how the designers of each prototype used specific technology affordances and how these were envisioned to contribute to children's ES engagement/learning. This analytic process yielded four overarching design themes. In keeping with the interpretive approach taken, the two authors regularly met to discuss the descriptions and the latent themes emerging, ensuring the primary text within the papers aligned with the themes.

4. Findings

A total of 31 papers were identified through the descriptive literature review described in Section 4.1, which all focused on the topic of ES, digital technology, and children. Of these, 20 were published at IDC, 7 at IJCCI, 3 at OzCHI and 1 in CHI.

4.1. RQ1: What are the publication trends and research genres of CCI research as it applies to ES?

4.1.1. Publication trends

The average number of **papers** published per year during the period analysed (2009–2023) was 2.07 (SD = 1.54). As Fig. 1 shows, apart from a peak in 2011 and 2020, the number of publications has remained relatively low. Furthermore, we found no relevant publications in 2009, 2012, and 2016.

An examination of the **authors** involved in the papers showed 124 unique contributing authors. Of these, eleven (consisting of 9% of all authors) had published more than one paper in the four venues in the paper corpus. Inspecting these authors further showed that nine co-authored two papers and two co-authored three in total. An analysis of authors' self-citations, measured through **backward and forward snowball referencing**, indicated that two thirds of the paper corpus did not include any self-citations (8 papers for backward referencing Bayley, Snow, Weigel, & Horrocks, 2020; Cumbo, Paay, Kjeldskov, & Jacobs, 2014; Desjardins & Wakkary, 2011; Dobal & Lalioti, 2021; Horn et al., 2011; Peters & Songer, 2011; Underwood et al., 2022; Zhang, Shrubsole, & Janse, 2010 and 13 papers for forward referencing Bayley et al., 2020; Bodén, Dekker, Viller, & Matthews, 2013; Brady, Jen, Vogelstein, & Dim, 2022; Cumbo & Iversen, 2020; D'Angelo, Harmon Pollock, & Horn, 2015; Dobal & Lalioti, 2021; Hirskyj-Douglas, Gray, & Piitulainen, 2021; Lamarra, Chauhan, & Litts, 2019; Mylonas, Hofstaetter, Giannakos, Friedl, & Koulouris, 2023; Peters & Songer, 2011; Underwood et al., 2022; Zhang et al., 2010, 2023). Looking at papers whose authors did self-cite, our analysis distinguished between papers that cited *ES research* and those *citing research in other topics*. From the papers citing ES research, 38% (12 papers) had self-referenced their past ES research (Adachi et al., 2013; Antle, Warren, May, Fan, & Wise, 2014; Cumbo & Iversen, 2020; Dillahunt, Lyra, Barreto, & Karapanos, 2017; Horn, Leong, Greenberg, & Stevens, 2015; Kawas, Kuhn, Tari, Hiniker, & Davis, 2020; Kynigos & Yiannoutsou, 2018; Logler et al., 2020; Mylonas et al., 2019, 2023; Vella, Dema, Soro, & Brereton, 2021; Zhang et al., 2023) and 45% (13 papers) had self-cited the corpus paper in ES research that they had subsequently carried out (Adachi et al., 2013; Antle et al., 2014; Antle, Wise, & Nielsen, 2011; Cumbo & Leong, 2015; Cumbo et al., 2014; Dillahunt et al., 2017; Horn et al., 2011, 2015; Kawas, Chase, Yip, Lawler, & Davis, 2019; Kawas et al., 2020; Mylonas et al., 2019; Silvis, Clarke-Midura, Shumway, Lee, & Mullen, 2022; Vella et al., 2021). Specifically, these papers averaged 2.83 (SD = 1.69; min = 1; max = 6) backward and 2.00 (SD = 1.78; min = 1; max = 7) forward self-citations on ES topics. Authors also self-cited research that was not connected to ES. This was found in 58% (18 papers) of the papers for backward referencing (Antle et al., 2011; Bodén et al., 2013; Brady et al., 2022; Cumbo & Iversen, 2020; Cumbo & Leong, 2015; D'Angelo et al., 2015; Hirskyj-Douglas et al., 2021; Horn et al., 2015; Kawas et al., 2019, 2020; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019; Logler et al., 2020; Mylonas et al., 2023; Sharma, Krishnaveni, Marianne, Netta, & Blessin, 2020; Silvis et al., 2022; Weibert et al., 2017; Zhang et al., 2023) and 32% (10 papers) for forward referencing Adachi et al., 2013; Antle et al., 2014, 2011; Desjardins & Wakkary, 2011; Horn et al., 2015; Kawas et al., 2019; Kynigos & Yiannoutsou, 2018; Logler et al., 2020; Sharma et al., 2020 and Weibert et al. (2017) highlighting that the papers were also motivated by other research agendas held by the authors.

4.1.2. Research genre

Fifteen papers (45%) referred to a **prototype evaluation** of a new bespoke technology developed by the researchers ((Adachi et al., 2013; Antle et al., 2014, 2011; Bayley et al., 2020; Bodén et al., 2013; D'Angelo et al., 2015; Dobal & Lalioti, 2021; Kawas et al., 2020; Mylonas

Fig. 1. Publications per year.

et al., 2019, 2023; Peters & Songer, 2011; Sharma et al., 2020; Underwood et al., 2022; Zhang et al., 2010, 2023)). Papers from this genre always included a design rationale. However, we note that only five papers reported the involvement of children or other relevant stakeholders in the design process as part of this; user involvement most often informed user requirements or feedback on an existing design direction (Antle et al., 2011; D'Angelo et al., 2015; Dobal & Lalioti, 2021; Kawas et al., 2019; Zhang et al., 2010). The child's **learning through the process of design or making** was identified in nine papers (29%) (Brady et al., 2022; Dobal & Lalioti, 2021; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019; Logler et al., 2020; Mylonas et al., 2019; Sharma et al., 2020; Underwood et al., 2022; Weibert et al., 2017). Grounded in constructionist theories of learning, this research orchestrated a learning process using technology as a tool to think through (e.g., Brady et al. (2022)), or as a supportive tool (e.g., Weibert et al. (2017)). **Empirical studies** that aimed to inform a new understanding of an ES practice, opportunity area, or methodology were detected in five papers (16%) (Cumbo & Leong, 2015; Cumbo et al., 2014; Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2015). Finally, four papers reported **design-oriented research** (12%) seeking to generate new theories and design opportunities through design methods (Cumbo & Iversen, 2020; Hirskyj-Douglas et al., 2021; Kawas et al., 2019; Vella et al., 2021), and there was only one **concept** paper advancing a new vision for an ES domain published in the corpus (Horn et al., 2011). We observe that none of the papers reviewed appeared to engage with children's own visions for technology design to empower them to inform ES through participatory design.

4.2. RQ2: Which user groups and contexts has CCI prioritised in its research?

In analysing the **geographical area** where the research took place, we found a trend in Western Regions: 45% of papers were from North America (nine from the USA Brady et al., 2022; D'Angelo et al., 2015; Horn et al., 2011, 2015; Kawas et al., 2019, 2020; Lamarra et al., 2019; Logler et al., 2020; Silvis et al., 2022, three from Canada (Antle et al., 2014, 2011; Desjardins & Wakkary, 2011), and one from a collaboration between USA and Canada (Peters & Songer, 2011)), 19% were from Europe (two from Greece (Kynigos & Yiannoutsou, 2018; Mylonas et al., 2019), one from each of Denmark (Cumbo et al., 2014), the UK (Underwood et al., 2022), Portugal (Dillahunt et al., 2017), Finland (Hirskyj-Douglas et al., 2021) and the Netherlands (Zhang et al., 2010)), 22% papers from Australasia (four from Australia (Bayley et al., 2020; Bodén et al., 2013; Cumbo & Leong, 2015; Cumbo et al., 2014), one paper from each of Japan (Adachi et al., 2013), China (Zhang et al., 2023), India (Sharma et al., 2020)), and 13% involved international research sites (one between the USA and UK (Dobal & Lalioti, 2021), between Germany and Palestine (Weibert et al., 2017), between Greece, Sweden and Italy (Mylonas et al., 2023), and Bhutan and Australia (Vella et al., 2021)).

Considering the **ages** of the children reported in the paper corpus, children ranged from two to 18 years old. Wishing to understand which age groups have been involved in this research the most, we plotted child age by the frequency of the ages appearing in the papers, visualised in Fig. 2. This analysis shows that researchers working at the intersection of ES and digital technology have tended to focus on the upper primary and lower secondary school ages with less of a focus on younger children and older teenagers. A closer examination on the **group of children** involved showed that none of the papers explicitly used a sampling strategy to target children based on the climate risks they faced, e.g., children in the Global South, children living in coastal towns or densely populated urban areas etc. Nonetheless, 12% of the papers (four papers) reported recruiting children from diverse socioeconomic and demographic backgrounds (Brady et al., 2022; Horn et al., 2015; Kawas et al., 2019; Logler et al., 2020). Additionally, one paper involving children from an underprivileged, marginalised group (Weibert et al., 2017) and another worked with special education needs school in the global South (Sharma et al., 2020) indicating an effort to benefit children who may otherwise not have the opportunity to participate in research.

Looking at the **context** the digital technology was intended to be used in, a total of two papers, constituting 6% of the paper corpus, did not explicitly define the intended context (Antle et al., 2011; Lamarra et al., 2019). Of the remaining papers, 45% (thirteen papers) focused on schools (Adachi et al., 2013; Antle et al., 2014; Bodén et al., 2013; Dobal & Lalioti, 2021; Kynigos & Yiannoutsou, 2018; Logler et al., 2020; Mylonas et al., 2019, 2023; Peters & Songer, 2011; Sharma et al., 2020; Underwood et al., 2022; Vella et al., 2021; Zhang et al., 2010), 16% (five papers) home (Bayley et al., 2020; Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011, 2015), 19% (six papers) outdoors (Cumbo & Iversen, 2020; Cumbo & Leong, 2015; Cumbo et al., 2014; Kawas et al., 2019, 2020; Zhang et al., 2023), and 9% (three papers) considered informal learning contexts namely aquariums, zoos, and clubs (D'Angelo et al., 2015; Hirskyj-Douglas et al., 2021; Weibert et al., 2017). One paper designed the research as part of a university-school outreach and thus the campus was the context (Brady et al., 2022).

Further, 51% of the papers (16 out of 31 in total) focused on children/teenagers without consideration of adult users when designing or researching the impact of ES interventions (Adachi et al., 2013; Antle et al., 2014, 2011; Bodén et al., 2013; Brady et al., 2022; Cumbo & Leong, 2015; Dillahunt et al., 2017; Dobal & Lalioti, 2021; Hirskyj-Douglas et al., 2021; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019; Peters & Songer, 2011; Sharma et al., 2020; Vella et al., 2021; Zhang et al., 2010, 2023). In schools, which was the most dominant

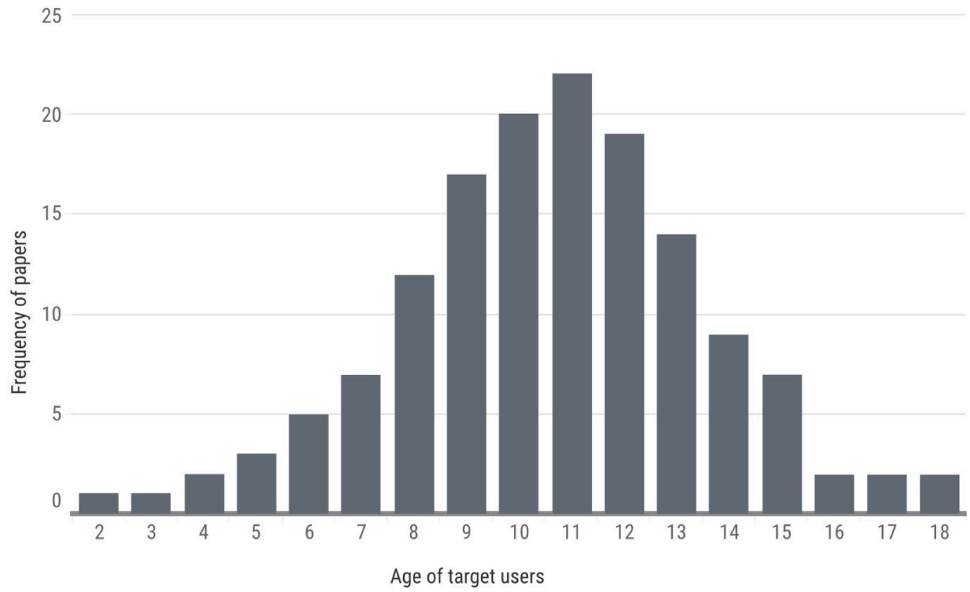

Fig. 2. Frequency of research involvement targeting children of specific ages (papers may be represented more than once based on the age range).

context, surprisingly only three papers presented a digital technology that actively involved the teachers in its design or use (Mylonas et al., 2019, 2023 and Silvis et al. (2022)), and one was designed to engage the entire school community (including teachers/students), introducing new stakeholders such as the energy manager of the school (Underwood et al., 2022). Aligning with the home focus mentioned above, except for one experimental study (Dillahunt et al., 2017), the rest all highlighted the importance of children and parents engaging together in sustainable actions. In contrast to the relational and shared use of technology anticipated in the home (e.g., Horn et al. (2011)), four of the six papers focusing on the outdoors engaged with the parental role (Cumbo & Iversen, 2020; Cumbo et al., 2014; Kawas et al., 2019, 2020) defining the parent either as a gatekeeper of children's outdoor activity, or scaffolding child-led explorations if and when needed.

4.3. RQ3: How has ES informed CCI research?

To examine the conceptual underpinnings of the papers, first, we considered whether the papers aimed to advance the link between ES and digital technology for children, thus evaluating the primary **research motivation**. This showed that about half of the papers (55% — 17 papers) were concerned with ES. The rest (45% — 14 papers) used ES as an application area to pursue a different research objective (Adachi et al., 2013; Antle et al., 2011; Bodén et al., 2013; Brady et al., 2022; D'Angelo et al., 2015; Hirskyj-Douglas et al., 2021; Kawas et al., 2019; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019; Logler et al., 2020; Peters & Songer, 2011; Sharma et al., 2020; Zhang et al., 2010), despite featuring a technology designed to promote child engagement with ES. Examples of this included: a TUI tangible user interface (hosting an ES game) to engage visitors in informal spaces (D'Angelo et al., 2015), testing the usability of an interactive map showing climate change impacts on species (Peters & Songer, 2011), or the role of a game authoring environment featuring an ES focus on constructionist learning (Kynigos & Yiannoutsou, 2018) Given their lose focus on ES, these papers lacked relevant theories, an issue we examine next.

From the dataset coded, 41% (13 papers) (Antle et al., 2014; Bayley et al., 2020; Cumbo & Iversen, 2020; Cumbo et al., 2014; Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011, 2015; Kawas et al., 2020; Mylonas et al., 2023; Vella et al., 2021; Weibert et al., 2017; Zhang et al., 2023) included a section with a **theory** that featured an environmental focus informing the research. The theories used originated from environmental education (Bayley et al., 2020; Horn et al., 2011; Kawas et al., 2019; Vella et al., 2021; Zhang et al., 2023), environmental psychology (Bayley et al., 2020; Cumbo & Iversen, 2020; Cumbo et al., 2014; Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011; Kawas et al., 2019; Vella et al., 2021; Zhang et al., 2023), HCI (relating to eco-feedback) (Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011, 2015), education and technology applied to sustainability (Mylonas et al., 2023), ecology (Cumbo et al., 2014; Dillahunt et al., 2017), circular design and sustainability

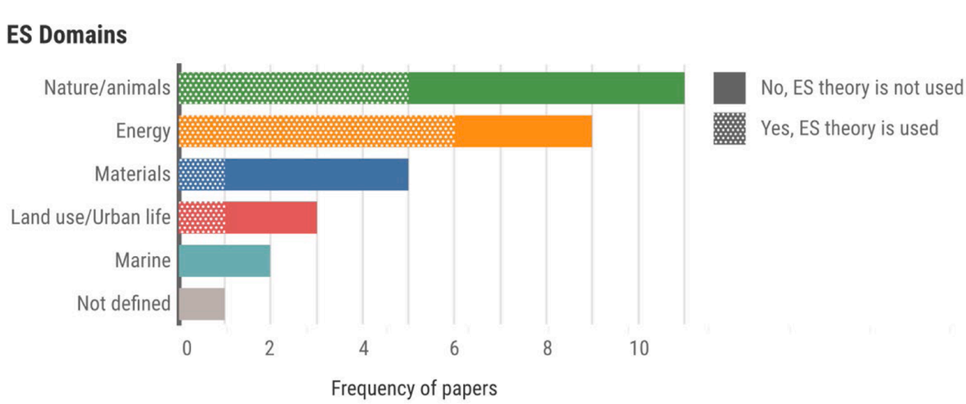

Fig. 3. Frequency of papers reporting on five ES domains and ES theories.

(Weibert et al., 2017), children's geography (Cumbo & Iversen, 2020), and policy (Bayley et al., 2020). Moreover, two papers, or 8%, imported theories from other disciplines to creatively reframe theoretical and analytical perspectives on children's engagement in ES and digital technology (Dobal & Lalioti, 2021; Silvis et al., 2022). An example of this was research from Dobal and Lalioti (2021) who motivated the importance of applying critical thinking, situated science learning and post-humanism to a climate education using these perspectives to inform the design of a new bio-material toy interacting with augmented reality. The remaining 16 papers in the corpus, constituting 51%, made no references to ES theories.

An examination of the **domains** covered in the corpus showed five domains also illustrated in Fig. 3. Presented in order by their prevalence, we summarise the aims underpinning CCI research within each domain with illustrative examples:

- '**Nature and animals'** is concerned with developing children's scientific understanding of climate change impacts on nature/animals, as well as their affective attachments (Adachi et al., 2013; Bodén et al., 2013; Cumbo & Iversen, 2020; Cumbo & Leong, 2015; Cumbo et al., 2014; Hirskyj-Douglas et al., 2021; Kawas et al., 2019, 2020; Peters & Songer, 2011; Vella et al., 2021; Zhang et al., 2023). For example, early CCI research aimed to trigger children's causal links between environmental conditions and vegetation, e.g., Adachi et al. (2013). More recent work has considered outdoor engagements with nature and animals to nurture attachments and future stewardship, e. g. Cumbo & Iversen, 2020; Hirskyj-Douglas et al., 2021 and Kawas et al. (2020).
- '**Energy'** aims to reduce children's energy consumption (Bayley et al., 2020; Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011, 2015; Mylonas et al., 2019, 2023; Underwood et al., 2022; Zhang et al., 2010). Research in the home has explored families' energy understanding, use and conservation e.g., Horn et al. (2011), contrasting with the digital technologies designed for schools aiming to promote conservation by engaging children in digitally mediated problem-solving e.g., Mylonas et al. (2019) and Underwood et al. (2022).
- '**Materials'** centres on learning how to care, repair, and reuse digital technologies and everyday objects (Dobal & Lalioti, 2021; Logler et al., 2020; Sharma et al., 2020; Weibert et al., 2017). For instance, taught young people how to upcycle plastic waste they found in their communities (Weibert et al., 2017). Logler et al. (2020) explored how young people engaged with the material process of dissembling a printer to suggest that disassembly offers generative possibilities for sustainability.
- **'Land use/urban living'** focuses on communicating the environmental trade-offs involved when using resources to plan/engage in rural and urban spaces (Antle et al., 2014, 2011; Kynigos & Yiannoutsou, 2018). For example, by simulating the energy implications and trade-offs associated with the diverse activities involved in urban living (Kynigos & Yiannoutsou, 2018).
- **'Marine'** seeks to show the impact of human activity on the marine ecosystem, with this work highlighting how overfishing or plastic waste affect the ocean resources available (Brady et al., 2022; D'Angelo et al., 2015).

In visualising the relationship between the ES domains found and the ES theories used, Fig. 3 shows that the two most prominent domains, i.e., nature/animals and energy, have engaged with theory the most.

4.4. RQ4a: What types of technologies have been used?

Our analysis shows that CCI research has explored **ten technology types**, with a strong focus on *eco-feedback* (Desjardins & Wakkary, 2011; Dillahunt et al., 2017; Horn et al., 2011, 2015; Mylonas et al., 2019; Underwood et al., 2022) embedded in either IoT or smart technology, followed by *Tangible User Interfaces (TUI)* always combined with simulation games (Antle et al., 2014, 2011; D'Angelo et al., 2015; Zhang et al., 2010). In addition to TUI, three papers reported on *tablet based games* (Bayley et al., 2020; Mylonas et al., 2023; Vella et al., 2021) and two papers researched games allowing for *full body interaction* as an input to the game environment (Adachi et al., 2013; Brady et al., 2022). Thus, overall, 30% of the papers in the corpus were concerned with games. Past research also used *off the shelf software and hardware*, such as maps, search engines, web-based animations, or a printer (Bodén et al., 2013; Logler et al., 2020; Peters & Songer, 2011; Weibert et al., 2017), which in a couple of papers was part of a broader maker/design process (Logler et al., 2020; Weibert et al., 2017). Three papers featured *game authoring* (Brady et al., 2022; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019), including a full body interaction approach (Brady et al., 2022), and one reported on a *programmable robot* (Silvis et al., 2022). *Mobile applications,* most with self-report features, were presented in five papers (Cumbo & Iversen, 2020; Kawas et al., 2019, 2020; Sharma et al., 2020; Zhang et al., 2023). Two novel technologies were also considered: *animal-involved technologies* (Hirskyj-Douglas et al., 2021) and a *bio-material toy combined with Augmented Reality* (AR) (Dobal & Lalioti, 2021). In fact, we found three instances of AR always combined with another technology: eco-feedback, bio-material toy, and off-the shelf technology (Bodén et al., 2013; Dobal & Lalioti, 2021; Mylonas et al., 2019). Finally, there were two papers in the dataset that did not speak back to a specific technology and was coded as 'not defined' (Cumbo & Leong, 2015; Cumbo et al., 2014).

Fig. 4 maps these technologies to the domains showing that energy has been dominated by eco-feedback technology, whereas mobile/self-report technologies have been applied only to the domain of nature/animals.

4.5. RQ4b: How has technology been designed to foster children's ES?

Having categorised the types of technologies used in the corpus we now consider four design themes the papers evoked to connect the use of technology to ES. We use selective examples to illustrate how the various technology types were used to instantiate these rationales, whilst pulling out relevant insights reported within the papers.

Making the hidden visible mobilises action: an important opportunity offered by technology was the ability to represent the use of resources, or natural processes, that typically remained hidden with the aim to mobilise sustainable action. *Eco-feedback* technologies were a vivid example of this by visualising the use of resources (e.g., water, energy) in built spaces to make people's resource magnitude/impact visible (Horn et al., 2015). While many of the papers recognised the challenge of motivating changes in energy consumption with these technologies offering speculative solutions, one paper provided empirical insights from the use of eco-feedback in the school context illustrating the time-intensive and multi-stakeholder collaboration required for this technology to foster energy conservation (Underwood et al., 2022). In a very different example (Dobal & Lalioti, 2021), 'Circular Species', a toy made from biomaterials was used to show children how a mammoth biodegrades when buried complemented with AR to illustrate the carbon cycle of the mammoth. After making this natural process visible, children went on to explore different types of biomaterials from which to make new objects.

Supporting the exploration of cause–effect relations: simulation games allow their players to experiment with different actions and observe their consequences. As applied to ES, the papers in the corpus employed games to model a *wide range of relationships* such as the impact of a changing climate on weather events and different types of vegetation (Adachi et al., 2013), the effect of different land planning choices on flooding (Antle et al., 2011) or the impact of short-term overfishing to maximise profits on the marine ecosystem (D'Angelo et al., 2015). Two games were designed to communicate *simple cause–effect relationships*

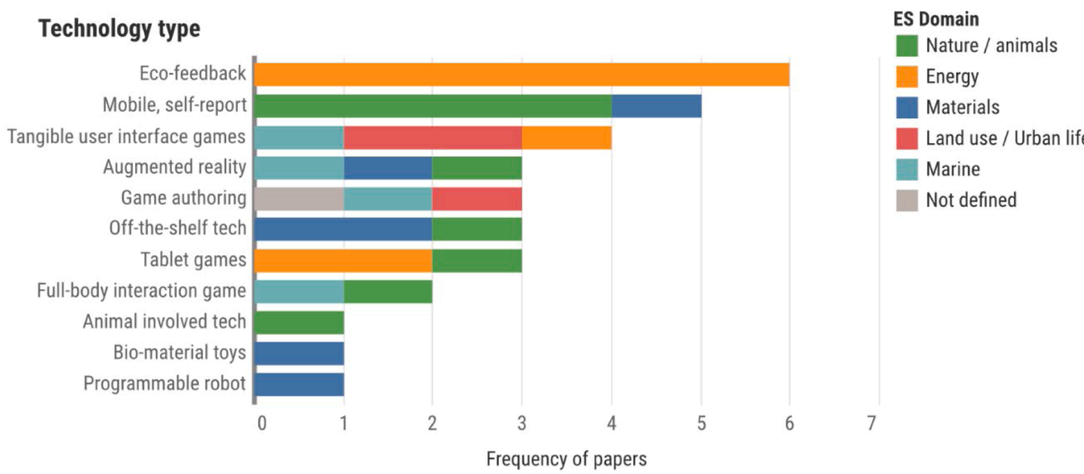

Fig. 4. Frequency of papers reporting ten different types of technologies, coloured by five ES domains.

(Adachi et al., 2013; Bodén et al., 2013) such as for example the effect of recycling on improving animal welfare (Bodén et al., 2013), while the majority modelled more *complex cause–effect relationships* (Antle et al., 2014, 2011; D'Angelo et al., 2015; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019; Zhang et al., 2010). Examples included 'Youtopia' that allowed the player to learn about and experiment with the individual and cumulative impact of different land planning activities on flooding (Antle et al., 2014), or a game that simulated the relationship between different energy types, environmental states and human welfare (Zhang et al., 2010). Notably, in this latter game, players whose energy choices negatively impacted on the environment affected the progress of others, thus highlighting the impact of individual action on the collective. To this end, several of the papers introduced the simulation games within a collaborative process designed to promote discussion, negotiation and reflection on values to inform game choices (Antle et al., 2011; Lamarra et al., 2019). Finally, with most games including a TUI, we note that the focus on physical interaction with TUI was motivated by other rationales not related to ES e.g., saving time, being intuitive, arousing curiosity (Antle et al., 2014; Zhang et al., 2010).

Making as a way of expressing and negotiating ES: technology was approached as a probe allowing children to express their understanding of the ES domain. Game authoring was used to this end as a "tool to think with" with the articulation of rules triggering opportunities for expression and negotiation (Brady et al., 2022; Kynigos & Yiannoutsou, 2018; Lamarra et al., 2019). In contrast to the simulation games reviewed above, whose rules and cause–effect mappings were determined by the designers, the papers in our corpus that took this approach placed the students in the role of the designer leaving the option for them to discursively decide what is right or wrong e.g., Kynigos and Yiannoutsou (2018). A challenge of this research centred on how to engage children in meaning making while using highly complex technology. This was addressed in Brady et al. (2022) by asking children to design low-fidelity prototypes the developers went on to code, whereas Kynigos and Yiannoutsou (2018) presented children with a 'half-baked' game 'PerfectVille' allowing them to revise this existing simulation more easily. Games authoring was always introduced in student teams to promote collaborative learning. As part of this, constructive conflict was sparked – centred on what to represent in the game and its social meanings – fostering the articulation, negotiation, and generation of their sustainability values.

Creating attachments and affective connections: the final design rationale that emerged aimed at moving beyond rational and scientific conceptions of ES to an affective appreciation and connection with nature and materials. It also employed the most diverse design sensibilities and technologies to accomplish this. In asking students to enact different plants with their bodies in a full body interaction game, Adachi et al. (2013) showed that students experienced empathy for plants whose health deteriorated due to climate change weather events. In a similar approach that fostered perspective-taking, Brady et al. (2022) found that students authoring games for other young children placed these children in different roles (e.g., polluter, fish) to evoke emotions in relation to the degradation of the marine ecosystem. Other research under this theme used mobile technologies to nurture attachments with nature and develop children's ecological identities. Cumbo and Iversen (2020) proposed technology to support children's sensemaking of their free outdoor play and thus child-led interaction with nature, whereas Kawas et al. (2020) and Zhang et al. (2023) designed and used mobile technology to bring children's attention to nature and thus strengthen this bond.

5. Discussion

Despite the importance of ES to children's education, previous systematic literature reviews sampling from the two flagship CCI venues (Interaction design and children 'IDC' conference and International Journal of Child–Computer Interaction 'IJCCI') have not identified ES as an active area of research (Giannakos et al., 2020; McDermott et al., 2022). This was confirmed in our descriptive literature review which sampled papers from the same venues. It is noted that our effort to broaden our corpus by searching for papers that positioned their ES contributions to CCI was not productive, and thus 27 out 31 papers in our corpus were published in IDC and IJCCI. Over the 14-year period reviewed the publications averaged under two papers yearly. There was also no upward trend to indicate growth in this activity. This aligns with findings from Høiseth and Van Mechelen (2017) in the domain of children's physical health and obesity, showing that CCI research published in the IDC conference was not commensurate to the scale of the problem. Given the timeliness and impact of climate change in children's lives, we argue that ES *should* be represented as a central theme in CCI's flagship venues, mirroring the growth of SHCI within the broader umbrella of CHI.

Following on from this, it is also pertinent to look at our paper corpus to identify existing ES scholars in search of emerging leaders. Our analysis shows that 124 authors have been involved in ES research – either by publishing in CCI flagship venues or speaking directly to the CCI community – during the 14-year period reviewed. Yet only eleven were repeat authors and those had published between two and three papers each. This appears to suggest that researchers presenting their research from the prism of CCI have engaged with ES very little. However, looking at whether the authors in our corpus cited their own *ES research* provides an additional, positive outlook. These papers had self-cited, on average 2.8 previous papers published in other venues before the CCI publication and had also self-cited their paper an average of two times papers since its publication. Importantly, the maximum ES-related self-citations for backward referencing were 6 and 7 for forward referencing indicating that at least one CCI author had an extensive publication record on ES. Showing that some researchers publish their ES research in a wider range of venues highlights the interdisciplinary communities CCI researchers ascribe to. However, a consequence of this dispersed activity is that it can limit the cumulative understanding needed for CCI to critically advance this important area, which has previously benefited other core CCI domains such as literacy (Giannakos et al., 2020). We thus suggest that future work bolsters the presence of ES within the flagship CCI venues. Moreover, our findings show the necessity for a wider literature review that moves beyond an HCI focus to consolidate relevant research activity concerned with children, ES, and digital technology.

Moving beyond the publication patterns of current CCI research to its content, we now consider CCI's contribution to ES to date. We do this through the lens of intermediate-level knowledge, which involves looking beyond specific instances of technological artefacts to distil and abstract the core design ideas underpinning them (Barendregt, Torgersson, Eriksson, & Börjesson, 2017). This approach, we believe, has the potential to offer generative knowledge that motivates future interaction design for children's ES. In line with this, our analysis shows that four design themes currently drive the design of digital technologies for children's ES: '*Making the hidden visible mobilises action*' uses technology to expose invisible aspects of the natural word (e.g., energy flows/consumption, biodegrading) with the view to inform children's sustainable actions within their environment; '*Supporting the exploration of cause–effect relations*' capitalises on the affordances of technology to simulate simple and complex relationships which children can explore to build their systems thinking and practice their skills; '*Making as a way of expressing and negotiating ES*' uses authoring technology and material objects as a creative resource that children can use to represent and express their understandings and values as they relate to ES; '*Creating attachments and affective connections*' uses technology to mediate children's affective understandings of ES and reinforces their connections with the natural/material world through physical engagements, often seeking to support ecological identities that foster future stewardship. CCI research has used ten different technologies with distinctive affordances to embody the design themes, in contrast to other systematic reviews that found a dominant technology type being applied within a challenge area, though it is noted that 30% of the papers reviewed concentrated on games (Høiseth & Van Mechelen, 2017).

Looking to the future, the remainder of this discussion inspects the patterns of current CCI research through the prism of ES, connecting them to the SDGs where relevant to spotlight which SDGs have received attention to date. Our analysis contributes five critical areas intended to consolidate and advance CCI's future ES research agenda.

5.1. Re-framing how ES research and design is carried out

The choice of research topics can be often driven by different agendas and priorities. In line with this, our findings showed that ES was not always a core challenge area for CCI with approximately half of the papers reviewed treating it as ancillary to another research aim. While we suggest there is a need to be transparent about these agendas from the onset, we also believe this can impede the field's progress to impact on children's ES, and thus appeal to future CCI researchers to adopt a *problem-focused lens* on this critical and timely issue. In alignment with past work (McDermott et al., 2022; Yarosh et al., 2011), we found that nearly half of the papers in the corpus were artefact-focused, i.e., presenting a technology prototype evaluation. Drawing from our own experiences, artefact-focused research offers opportunities to be in dialogue with theory: in using theory to inform design and generating it through empirical observations (Eriksson et al., 2022). Applied to ES, artefact-focused research can thus play a crucial role in shaping the nascent theoretical understandings of children's digitally mediated learning and engagement. Our experience also shows that artefact-focused research can be a ripe context for undertaking design-oriented research that brings children into the design process to negotiate and define the roles that digital technology could play for ES. However, in line with other systematic reviews within CCI showing the restricted use of theory in research (Høiseth & Van Mechelen, 2017; Yarosh et al., 2011), about 40% of the papers within the corpus used ES theory to inform the research. Further inspecting the theories used shows they are driven by the two most mature ES domains, highlighting an important gap in those still emerging, e.g., materials. Surprisingly, given CCI's learning and education focus (Giannakos et al., 2020), theories from the discipline of environmental education were only referenced in a small number of papers, stressing the importance of interdisciplinary collaborations that have been so crucial to past CCI work (Giannakos et al., 2020). Similar gaps are found when looking at the research genres of the papers and the scarce design-oriented research to date, with only a few papers involving children in shaping technology design. We propose that CCI researchers, owing to their longstanding expertise in participatory design (PD) and design methods (Giannakos et al., 2020; McDermott et al., 2022), are ideally situated to lead both design speculations on children's critical futures at a time of climate change and design-oriented research serving to advance technology that engages children with ES in new and meaningful ways.

5.2. Expanding users, roles, and contexts

The research we reviewed predominantly concentrated in the upper primary and lower secondary school ages, a finding that has been previously shown to apply to the CCI field more broadly (Høiseth & Van Mechelen, 2017; Yarosh et al., 2011). In recognising that children's ecological stewardship is an enduring project that must be nurtured over the child's lifetime, we raise the need to involve both younger children and older teenagers. Future work could consider which domains and ES strategies are relatable to children of different ages, and additionally explore ways to engage older teenagers – who are increasingly participating in activism – in sustainable actions. Looking at the geographical areas reported in our corpus, the largest group of children involved to date have been from the Global North with the majority living in North America, Europe and Australia. Of these children, none were selected based on their risk of climate change impacts. While we do not wish to undermine CCI's current efforts, we also suggest there is a need to understand what children at risk of climate change impacts want from digital technology. Both IPCC and UNICEF reports (Pörtner et al., 2022; UNICEF, 2021) indicate the regions and children at the highest risk offering one way to identify these groups. It is here where PD could be used to involve children and their communities to co-design new ways to adapt and cope with climate change. Moving in this direction, CCI researchers will need to re-align themselves with PD's critical origins engaging with the effects of colonialism, and current forms of social order/logics on people/nature, whilst working with these communities to identify creative ways of expression that foreground their heritage and knowledge base (Nxumalo et al., 2022).

Our examination of the contexts of CCI research shows that almost half of the papers focused on schools, with the rest spread across the home, outdoors, and other informal learning contexts. While it is not surprising that schools have been a focus, strikingly, teachers rarely participated in the use of the technology, while research in the outdoors interpreted the parent's role as one that *facilitates* the child's technology use and nature engagement. This was also evident in the design of the ES technologies themselves, which was always centred on the child. Earlier, we have presented ES as a collective and interdisciplinary effort with emerging research showing the critical importance to involve children *and* adults alike in this collaborative project (Dunlop et al., 2022). For example, familial collaboration results in a multiplying effect for ES behaviours, as they become integral to family relationships and values (Parth, Schickl, Keller, & Stoetter, 2020). We do not suggest that such collaborations will be easy, but we also think they are necessary when striving to support children's authentic sustainable actions in the world. One paper (Underwood et al., 2022) in our corpus illustrated the multi-stakeholder and long-term efforts required: in this work teachers and children used eco-feedback and internet of things technology to identify energy inefficiencies in the school which were then followed up with the support of the broader school community, e.g., energy manager. Moving away from the paradigm of designing for the child to one that brings communities together, we believe that CCI's recent research in maker spaces and fabrication could provide important insights into how intergenerational teams can collaborate toward a common sustainability goal.

5.3. Enabling multidomain systems-thinking

Our review found that CCI papers to date have focused on five ES domains: nature and animals (*SDG15 life on land*), energy (*SDG7 affordable and clean energy*), materials (*SDG12 responsible consumption and production*), land use/urban life (*SDG11 sustainable cities and communities*), and marine ecosystems (*SDG14 life below water*). We show that some of these domains are less developed than others and thus warrant further attention from CCI. Of particular importance are 'materials' which are all around us and are a major contributor of household waste (Hawken, 2017), yet only five papers presented a focus on how to upcycle/care/biodegrade materials. Furthermore, there are yet several ES domains still to be explored in CCI, such as transportation (including the extraction of fossil fuels and low-carbon alternatives) and the food system (including food waste and the impact of various agricultural practices, e.g., on greenhouse gas emissions, deforestation, land degradation, waterway pollution). Not only are transportation and food systems both associated with significant environmental impacts but are also domains where young people, especially teenagers, can make everyday choices to mitigate said impacts (e.g., as suggested by Poore and Nemecek 2018), so are fruitful areas for future CCI research.

Alongside the gaps in the domains, we also found that current work has treated ES domains as discrete and thus failed to stress their influence on each other. We use selective examples to illustrate how digital technology could reinforce their interdependence. E.g., some papers concerned with children's environmental stewardship (Cumbo & Iversen, 2020; Kawas et al., 2020) did not make explicit links to the human systems responsible for the degradation of nature (e.g., transportation, material mining). Thus, children who were building attachments with nature would not necessarily make the connection that they too are actors in the same systems from which they seek to protect nature. Similarly, papers about the health of marine ecosystems (Brady et al., 2022; D'Angelo et al., 2015) made links to household waste but not to other human-driven domains that contribute to the problem, like agriculture, which is the number one polluter of rivers in the UK for example (Government (2018). Of the papers we reviewed, we found that simulation games were being used to engender complex systems thinking (a recognised affordance of these technologies; Hmelo-Silver, Jordan, Eberbach, & Sinha, 2017; Verhoeff, Knippels, Gilissen, Boersma, & Kerst, 2018), which we argue could also be applied to show the interdependencies between ES domains.

Systems thinking *within domains* should also be extended to systems thinking *within the three pillars of sustainability*. Similar to Scuri et al. (2022)'s review of SHCI research, we found that research touched either on only one pillar in isolation (usually the environmental pillar, e.g., Adachi et al. (2013) and Kawas et al. (2020)) or on two of the pillars (usually social and environmental, e.g., Antle et al. (2014) and Kynigos and Yiannoutsou (2018)). A few papers successfully made connections between the economy and the environment, such as D'Angelo et al. (2015), who used a simulation game to illustrate how unbridled economic growth of the fishing industry would ultimately lead to a depletion of fish as a resource. Yet, D'Angelo et al. (2015) did not make the connection to the social/societal consequences, thereby not connecting all three pillars of sustainability. This brings up new design challenges for the field of CCI, to explore how complex relationships can be successfully communicated to children to foster systems thinking and problem solving. There is evidence that this is possible; prior research has shown that children as young as three years old can grasp basic principles of supply and demand and how their decisions can affect this (Leiser & Halachmi, 2006; Stonehouse, Huh, & Friedman, 2022).

5.4. Striving for children's sustainable action

Most papers in our review described technology designed to foster children's understanding of the impact of human actions on ES, e.g., through supporting the exploration of cause–effect relationships. However, whilst the importance of interventions enabling *sustainable actions and decision making* has been raised in both SHCI (Knowles et al., 2018) and education (Monroe et al., 2008), we found fewer papers that fostered meaningful, real-world action (*SDG13 Climate action*). An illustrative example of this was Weibert et al. (2017), who explored community makerspaces to nurture upcycling skills and habits in children and families. Another example was Underwood et al. 2022 who engaged entire school communities in actively monitoring and analysing their energy use, ultimately leading to an average energy reduction of 5% through targeted changes in the schools. A key feature of Weibert et al. (2017)'s and Underwood et al. (2022)'s approach is that they situated technology and learning *in-place*, building on theories of interconnectedness (Lehtonen et al., 2018). Eco-feedback technologies may be particularly poised to do this because they make users' hidden energy use visible through data visualisation *from* the environment *in* the environment. Motivating our earlier call to design for communities, both papers (Underwood et al., 2022; Weibert et al., 2017) ensured the technology was embedded within a community committed to sustainable long-term change. Many eco-feedback initiatives have not been as successful, not only because users lack understanding of what energy units (e.g., in kW/h) mean in relation to their consumption, but also because they clash with values and habits of the family or community to promote longevity of ES behaviours (Strengers, 2011). A challenge for CCI research going forward is to explore how to cultivate long-term sustainable action, e.g., through situated, 'in place' approaches, that champion collaboration between adults and children, as observed in this past work (Underwood et al., 2022; Weibert et al., 2017). The nature/animal domain could be a fruitful direction to this end: whilst several of papers situated learning *in-place* outdoors (e.g., Kawas et al., 2020), they did not connect these experiences with specific sustainable actions that children can make in-place, nor did they foment shared experiences between children and adults that may have promoted longevity of the experience.

5.5. Apply CCI's engrained interdisciplinary skills and values to future ES research

Our discussion so far has focused on how CCI can expand its research agenda on ES by bringing ideas from ES into existing research CCI activity. It is equally important, however, to recognise that CCI has a lot to offer to ES through its technologies, learning theories and design lenses. Most notably, constructionism has been a driving and diachronic interest within the CCI research (Giannakos et al., 2020). Following from this, several papers in our corpus used physical computing or games authoring to foster children's learning. However, with many of them treating ES as an application area, we suggest there is an unexplored opportunity to show how these longstanding theories and technologies advance our understanding of constructionist *ES learning*. In a different example (still on theories), we found two papers that introduced theories from the social sciences, critical studies, and learning science disciplines into ES to argue for developing a novel perspective on ES and the digital (Dobal & Lalioti, 2021; Silvis et al., 2022). These examples show how CCI researchers' interdisciplinarity can offer a unique vantage point through which to creatively rethink the perspectives that will guide future research in children's ES and the digital, while strengthening our earlier call for more CCI research informed by theory and generating theory.

Throughout this discussion, we have argued for the need to draw on the CCI community's rich knowledge of PD, for instance to critique how digital technology is designed for ES and challenge who this technology seeks to benefit. The articulation and negotiation of values has been always a core part of a PD process and indeed values are expressed in the very fabric of technology design (Iversen, Halskov, & Leong, 2012). Many of the papers we reviewed, particularly simulated or authored games, reported an appreciation for values with children using the digital technology to make and challenge value-laden choices about their simulated world. Nonetheless, social justice was not reflected in this current work despite the climate inequalities globally and locally as mentioned earlier (UNICEF, 2021). Through CCI's existing engagement with values, we believe our community has an important role to play in bringing a climate justice focus into children's digital technologies. PD could also provide a vital approach to involve children in critical discussions centred on the extraction logic underlying capitalism extending to the technology domain. Within our paper corpus, this perspective on technology was best exemplified by Silvis et al. (2022): using a feminist ethics of care lens the authors explored how notions of care and repair were introduced and used by pre-schoolers in relation to their robots. Under the material domain, there were key works in our paper corpus that explored the use of biodegradable materials (Dobal & Lalioti, 2021) and composting (Sharma et al., 2020), dissembling and repairing technology (Logler et al., 2020) and making new objects from waste (Weibert et al., 2017). This existing activity offers the opportunity to involve children in such value-centred discussions to explore their relations with capitalism, critique the resources used when designing technologies, and negotiate their socio-cultural perceptions as they relate to prolonging the use/reuse/repair of their digital technologies. As one of the studies vividly showed (Sharma et al., 2020) socio-cultural perceptions from children and parents alike are equally important to understand as they can create barriers to children engaging in these activities.

6. Conclusion

Climate change is the most urgent issue of our time. Children's engagement with ES can support them to transition into future stewards of our planet. In contrast to recent concerns about the impact of SHCI research without necessary changes in policy to enact this research (Bremer et al., 2022), we argue that children's ES learning has the potential to profoundly impact on the future roles they take in society. As digital technology is intrinsically embedded in children's lives, there is little doubt about the role it is poised to play in children's engagements with ES, and we have argued that the CCI community's value-driven agenda, as well as its focus on children's learning, makes it well placed to take a leading role in this respect. The aim of this paper was to describe how CCI has engaged with ES to date, by conducting a descriptive literature review over 13 years.

An examination of publications in CCI's flagship venues shows that ES is an emergent CCI topic. While recognising the diverse disciplines that inform CCI, we also propose that a stronger representation of ES within HCI can contribute toward a coherent and future-oriented programme of research that interacts with SHCI more broadly. As evidence of this, our analysis of existing research activity advances four design themes showing how distinctive features of ten technology types have been used to support children's ES in this field, namely by '*making the hidden visible mobilises action*', '*supporting the exploration of cause–effect relations*', '*making as a way of expressing and negotiating ES*', and '*creating attachments and affective connections*'. Building on these themes, we elaborate five opportunity areas that serve as a 'call to action' for the CCI community to (i) *reframe how ES research and design is carried out* by grounding the research in critical and participatory accounts of ES, (ii) *expand the users, roles, and contexts in ES research* to involve communities at risk of climate impacts, moving beyond a child-centric focus and widening the age groups currently involved, (iii) *enable multidomain systems thinking through technology* through a re-orientation toward underrepresented domains and an interconnected systems thinking approach, (iv) *strive to enable children's sustainable actions* by moving toward digital interventions that foreground action in tandem with knowledge and, (v) *apply CCI's engrained interdisciplinary skills and values to future ES research,* through an audit of CCI's strengths.

Intended for those working on ES *and* new researchers wishing to enter this domain, we hope our review offers the needed roadmap to bring the interdisciplinary skills of the CCI community into the domain of ES and expand CCI research into new directions that advance children's engagements of ES with the use of new digital technologies.

Declaration of competing interest

There are no conflicts of interests to declare

Data availability

No data was used for the research described in the article.

Selection and participation

This research did not involve children.

Appendix

Year	References
2010	Zhang et al. (2010)
2011	Antle et al. (2011), Desjardins and Wakkary (2011), Horn et al. (2011) and Peters and Songer (2011)
2013	Adachi et al. (2013) and Bodén et al. (2013)
2014	Antle et al. (2014) and Cumbo et al. (2014)
2015	Cumbo and Leong (2015) and Horn et al. (2015)
2017	Dillahunt et al. (2017) and Weibert et al. (2017)
2018	Kynigos and Yiannoutsou (2018)
2019	Kawas et al. (2019), Lamarra et al. (2019) and Mylonas et al. (2019)
2020	Bayley et al. (2020), Cumbo and Iversen (2020), Kawas et al. (2020), Logler et al. (2020) and Sharma et al. (2020)

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Year	References
2021	Dobal and Lalioti (2021), Hirskyj-Douglas et al. (2021) and Vella et al. (2021)
2022	Brady et al. (2022), Sharma et al. (2020) and Underwood et al. (2022)
2023	Mylonas et al. (2023) and Zhang et al. (2023)

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