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Building user-driven climate adaptation products

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Analysis

Keywords:

Posted Date: February 17th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-5426878/v1

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Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Nature on June 10th, 2026. See the published version at https://doi.org/10.1038/s41586-026-10555-y.

Abstract

Climate adaptation products have traditionally been developed using a supply-driven model reliant on available climate information, leading to usability gaps. To better meet user needs, the climate services field has recognized a need to shift towards a demand-driven model emphasizing co-production, that is, user-driven, scientifically informed products created through shared knowledge practices. However, co-production can be challenging, especially for researchers unfamiliar with the approach or for digital and software-based products with complex user needs. User-centered design, from the human-computer interaction field, offers a process that could complement co-production approaches to product development, yet its potential remains underexplored. Here we show how user-centered design can integrate into, and strengthen, co-production approaches for building user-driven climate adaptation products. Through a systematic review of co-production and user-centered design literature, we identify key processes, mechanisms, and best practices for both approaches. Our findings offer practical guidance for researchers and propose an integrated approach for developing climate adaptation products that are useful, usable, and used.

Main text

Climate change is reshaping societal and ecological systems, and with 2024 now the first full calendar year above 1.5°C since pre-industrial times, information that supports adaptation to climate risks is increasingly urgent[9-12]. This need has accelerated demand for climate services, products, and tools ("climate products") that support climate-informed decisions[1, 3]. Despite the growth of climate products, many have fallen short of initial expectations[1, 13-15].

This partly reflects a one-directional, supply-driven model in which "developers" (often scientists and researchers) prioritize supplying better data and assume that more information will drive improved decision-making and action[1, 2, 15, 16]. Supply-driven climate products are scientifically driven but typically misaligned with user needs and decision requirements, limiting uptake and use[1, 2, 15, 17].

The "usability gap" describes the mismatch between supplied information and what "users" of climate products need[2, 4, 18]. The usability gap for climate products is exacerbated by fragmented product development across organizations and by diverse users and stakeholders with varying expertise and decision needs[1, 4, 19, 20]. Here, "stakeholders" are those who impact or are impacted by the decisions and processes relevant to a climate product, and they often, but not always, overlap with users[21].

Climate products that support adjustment to climate change ("climate adaptation products") face added challenges in supporting user understanding and communicating uncertainty in forward-looking climate data[8, 22]. Consistent with these challenges, prior research suggests that climate adaptation products often fall short in supporting adaptation planning and decisions due to a usability gap[23].

To address this usability gap, climate product development is increasingly shifting toward a demand-driven model that builds around user needs to deliver scientifically informed products that are useful, usable, and used[1, 15, 24]. Research on building user-driven climate products, particularly in climate services, has converged on the transdisciplinary theory of co-production[3, 4, 7, 25-27]. Co-production encompasses a broad concept of engagement anchored in joint knowledge creation and problem-solving[6, 13, 27, 28]. In practice, co-production is applied flexibly, enabling it to fit specific contexts and draw from other disciplines[5, 6, 25, 29].

One conception of co-production is a narrower, more normative approach focused on developing usable products through an iterative, interactive process[5, 29]. However, applying co-production for building user-driven climate adaptation products can be difficult because the theory is broad and offers limited guidance for context-specific implementation[5, 30, 31]. This is especially true for developers new to co-production or those building digital or software-based climate adaptation products, as these products face distinct usability, visualization, technical, and data constraints[8, 16, 20, 32]. With climate services still emerging and standards limited, there is an opportunity to assess co-production approaches for climate adaptation product development and test complementary approaches, especially for digital and software-based products[29, 30].

Human-computer interaction, an interdisciplinary computer science field that studies how users interact with technology, has seen limited crossover with climate services but could offer valuable lessons for building digital and software-based climate adaptation products[2, 14, 33]. Approaches within the field overlap with co-production and reflect a long tradition of user-oriented research and pragmatic design[2].

User-centered design is a human-computer interaction approach that incorporates users throughout product development[2, 8]. Used in the technology industry for decades, it encompasses practical mechanisms and practices across the product development process, from ideation to evaluation[2, 14]. For climate adaptation products, user-centered design can support building products that help users interpret scientific information, navigate uncertainty, and make informed long-term decisions[2].

Co-production approaches to product development could benefit from integrating user-centered design processes, mechanisms, and practices[2]. This integration can facilitate a more user-driven process, address distinct challenges in building digital and software-based climate adaptation products, and provide developers with more practical, flexible guidance[2].

In this Analysis, we systematically review co-production and user-centered design approaches to climate adaptation product development, distilling key processes, mechanisms, and practices. We then use this mapping to identify an integration framework and show how an integrated approach can support user-driven development of digital and software-based climate adaptation products.

Co-production approach

Normative and descriptive objectives shape how co-production is implemented, from building usable tools to empowering groups or analyzing how knowledge is produced[5, 29, 34, 35]. We take a normative lens and focus on a co-production approach aimed at product development and more specifically, the building of user-driven climate adaptation products[5]. With this in mind, we use the Vincent et al. (2018) co-production approach to producing usable science[5] (Fig. 1). This approach to co-production involves a continuous cycle of five stages: *Identify Actors & Build Partnerships*, *Co-Explore Need*, *Co-Develop Solution*, *Co-Deliver Solution*, and *Evaluate*[5] (Table 1). These stages circle around an inner cycle of continuous knowledge exchange, monitoring, and learning along with a process driven by principles of inclusiveness, collaboration, and flexibility[5, 36] (Fig. 1). Together, the Vincent et al. (2018) approach provides a practical basis for understanding co-production for product development and for analyzing its mechanisms and practices[5].

[**Fig. 1 | Co-production process for product development**]

[**Table 1 | Co-production stages for product development**]

Co-production elements

Co-production is widely discussed across literature related to climate adaptation products, and our review highlights this diversity through the elements (mechanisms and best practices) identified across the five co-production stages. Supporting background on climate services, user needs, and co-production is provided in the Methods.

There were 24 mechanisms applied across one or more of the five co-production stages, categorized as 10 artifacts, 9 activities, and 5 actors (Extended Data Table 1). Stage-agnostic mechanisms were often common techniques such as surveys, interviews, workshops, and focus groups (Extended Data Table 1). Stage-specific mechanisms placed greater emphasis on communication (for example, newsletters), capacity building (for example, training sessions), and documentation (for example, stakeholder interaction manuals) (Extended Data Table 1).

There were 64 best practices across the co-production stages, including those used to build effective products and those developers identified retrospectively as valuable (Extended Data Table 2). There are a few broad themes that connect many of these best practices. The first theme focuses on understanding, and the importance of comprehending the co-production process, as well as the capabilities and goals of developers and the needs and priorities of stakeholders and users. The second theme emphasizes communication, highlighting the importance of diverse mechanisms and opportunities for exchanging information, engaging with stakeholders and users, sharing results and progress, and gathering feedback. The third theme addresses iteration, stressing the importance of testing numerous iterations of products, using feedback to continuously refine plans and products, and maintaining flexibility and openness throughout the co-production process. The fourth theme centers on evaluation, particularly regarding whether the final climate adaptation product delivered is both usable

and beneficial to users and their needs. In addition to these four key themes, there are numerous other best practices that developers consider vital for implementing an effective co-production process and building usable climate adaptation products.

User-centered design approach

The user-centered design process typically includes planning, understanding context and user needs, defining requirements, designing solutions, prototyping, and testing[37, 38]. Although implementation varies, user-centered design has been codified by organizations such as the International Organization for Standardization (ISO)[39]. For this paper, we adopt ISO's user-centered design approach[39] (Fig. 2). This approach involves an iterative process divided into five stages: *Plan Process*, *Understand Context*, *Specify User Requirements*, *Produce Solutions*, and *Evaluate Solutions*[39] (Table 2). ISO's user-centered design approach emphasizes prototyping multiple solutions in the *Produce Solutions* stage and formal user-centered evaluation, including usability testing, in the *Evaluate Solutions* stage[38, 39]. If evaluation in the *Evaluate Solutions* stage shows the product does not meet requirements set in the *Specify User Requirements* stage, the process returns to an earlier stage to address the gaps[37, 39] (Fig. 2). As with co-production, we use this user-centered design approach to categorize and analyze mechanisms and practices.

[**Fig. 2 | User-centered design process**]

[**Table 2 | User-centered design stages**]

User-centered design elements

User-centered design is widely used in climate and sustainability contexts but appears less often than co-production in literature related to climate adaptation products; nonetheless, our review identified elements (mechanisms and best practices) mapped across the five user-centered design stages. Supporting background on human-computer interaction and user-centered design is provided in the Methods.

There were 41 mechanisms applied across one or more of the user-centered design stages, categorized as 19 artifacts, 21 activities, and 1 actor (Extended Data Table 3). Stage-agnostic mechanisms, similar to those in co-production, were often common techniques such as interviews, surveys, workshops, and focus groups (Extended Data Table 3). Stage-specific mechanisms span each stage and provide a range of mechanisms to guide developers through the user-centered design process (Extended Data Table 3). For some stage-specific mechanisms, there are sub-mechanisms such as different prototyping mechanisms that provide greater customization depending on the developers' goals or the type of product being developed (Extended Data Table 3). Several mechanisms recur across stages and appear core to user-centered design. One of them is the context-of-use during the *Understand Context* stage, which is a central document that guides work on understanding user needs and organizes information on product or user context (Extended Data Table 3). Another is the user requirements specification

during the *Specify User Requirements*, which organizes developer, user, and stakeholder requirements and provides a reference for the product design and evaluation (Extended Data Table 3). Prototypes are also essential, especially during the *Produce Solutions* stage, and the process entails frequent iteration using a mixture of low- and high-fidelity prototypes (Extended Data Table 3). Lastly, the *Evaluate Solutions* stage is a critical juncture for the user-centered design process with multiple mechanisms for testing usability and utility and for evaluating whether the final product delivered can be considered successful (Extended Data Table 3).

There were 45 best practices across each user-centered design stage that contributed to an effective user-centered design process or successful product (Extended Data Table 4). These practices reveal broad themes similar to those identified in co-production. The first theme emphasizes understanding and the importance of comprehending the process, problem, goals, assumptions, characteristics, and success metrics. The second theme focuses on communication and collaboration with diverse interdisciplinary teams, users, and stakeholders. The third theme highlights iteration and the value of rapid and continuous prototyping, testing, feedback, and improvement. The fourth theme emphasizes methodicalness, and the significance of a systematic approach to organizing insights, validating findings, steering the process, and evaluating products. These themes are further complemented by connecting ideas in the user-centered design literature, such as accessibility, inclusivity, and prioritization.

Integration approach

The overlap in processes, mechanisms, and best practices highlights strong synergies between co-production and user-centered design[2]. Though the exact language present in each approach varies, co-production approaches to product development already include many aspects of user-centered design. For example, there are analogous mechanisms such as interviews, focus groups, and prototypes as well as best practices such as establishing interdisciplinary teams, working extensively with users, understanding the problem and goals, developing multiple prototypes, and testing the final product. Even the stages within each approach's process show a similar structure and flow starting from planning and exploration of the problem context to building and evaluating the product (Fig. 1 and 2).

Although co-production and user-centered design overlap, integrating user-centered design can add distinctive strengths, improving salience, credibility, and legitimacy and addressing underdeveloped areas in co-production[2]. User-centered design processes, mechanisms, and practices help ensure that user input and needs are more effectively captured and incorporated, thereby increasing the relevance and contextual fit of climate adaptation products[3, 40, 41]. Likewise, user-centered design can make user engagement more structured, standardized, and transparent, which can strengthen trust and improve perceptions of impartiality and fairness[3, 17, 42-44]. Complementing these process-level strengths, user-centered design also contributes granular mechanisms for prototyping and testing, a stronger emphasis on systematic usability evaluation, and formal documentation tools such as context-of-use and user requirements specifications[45, 46]. These established mechanisms and practices, well suited to digital

and software-based products, can help developers tailor co-production processes for online and technology-enabled contexts[8, 32].

Beyond these practical benefits, integrating user-centered design also presents an opportunity to reshape power dynamics. While co-production processes aim to center user needs, they can inadvertently reproduce unequal power relationships based on expertise or institutional authority[47, 48]. User-centered design offers mechanisms and practices that can help co-production center user needs and shift aspects of decision-making authority from developers to users[48]. Collectively, these benefits suggest that embedding user-centered design in co-production can improve usability while advancing more salient, credible, legitimate, and equitable climate adaptation product development.

Co-production approaches to product development can integrate user-centered design in two primary ways. First, through a selective integration, user-centered design can expand the toolkit of available mechanisms and practices available during a co-production approach to product development. Using this type of integration, developers can selectively pick and choose user-centered design mechanisms or practices as needed during different co-production stages. For example, during the co-production *Co-Explore Need* stage where the goal is to understand decision need, user-centered design mechanisms such as context-of-use or user scenarios could be useful and used. Second, through a holistic integration, user-centered design can be embedded as a complete secondary process during a co-production approach for product development. This type of integration can be especially helpful for developers who are at the product-building stages of co-production and need to narrow down from a broader co-production process and focus on building tangible product or product features. For example, an entire user-centered design process can be embedded during the co-production *Co-Develop Solution* stage to explicitly and pragmatically guide the development of a digital or software-based climate adaptation product before returning to the broader co-production process. Regardless of integration type, user-centered design can give developers flexible, tangible mechanisms and practices that support user-driven climate adaptation products.

Integration framework

To support practical implementation, we propose a concise integration framework for incorporating user-centered design into co-production when developing digital or software-based climate adaptation products. Integration can be selective (adding user-centered design mechanisms to specific co-production stages) or holistic (embedding a full user-centered design process within part of the co-production process). The following guidance provides a starting point for applying either integration:

- **Deepen Familiarity with User-Centered Design:** Deepen familiarity with user-centered design processes, mechanisms, and practices to clarify integration options and where user-centered design can add value within co-production.
- **Map Co-production Process:** Map where the project, or broader product development effort, sits in the co-production process, even if a formal process has not begun, to guide which integration and

user-centered design mechanisms or practices are most relevant.

- **Assess Constraints:** Assess time, funding, and engagement capacity, since constraints such as limited time or unclear requirements shape whether selective or holistic integration is feasible and which user-centered design mechanisms and practices are appropriate.
- **Identify Desired Outcomes:** Identify desired outcomes such as rapid delivery, usability, or equitable engagement to help determine the integration and the user-centered design mechanisms and practices needed to achieve intended outcomes.
- **Decide Which Integration:** Decide whether selective or holistic integration fits best based on project stage, constraints, and desired outcomes, then use that choice to guide which user-centered design mechanisms and practices to apply, where to apply them, and how extensively.
- **Adjust As Needed:** Adjust the integration approach and user-centered design mechanisms and practices as feedback and needs evolve, remaining flexible and open to modification.

By emphasizing process awareness, intentionality, and flexibility, this integration framework provides a practical entry point for developers to tailor the integration of user-centered design into co-production.

Case examples

To demonstrate the value and variability of integrating user-centered design into co-production, we present two illustrative examples of climate adaptation product development: Europe-based Project Ukko and the U.S.-based Strategic Conservation Assessment (SCA) Tool. Project Ukko explicitly applied a full user-centered design process, while the SCA Tool implicitly incorporated selective user-centered design mechanisms without formally naming them[7, 10, 49]. Together, these examples illustrate holistic and selective integration. We also use the integration framework to show how it can be applied in practice.

Project Ukko, a seasonal wind-speed forecasting tool for the wind energy sector, exemplifies explicit, holistic integration of user-centered design within co-production[10]. The interdisciplinary project team brought together climate scientists, designers, stakeholders, and users, and employed a co-production approach that incorporated co-design, co-development, and co-evaluation throughout the product development process[10]. Through participatory approaches such as continuous communication, stakeholder workshops, and reciprocal knowledge exchange, the team applied co-production mechanisms to build shared understanding, define user needs, and incorporate user perspectives into the product's design[10]. At the same time, they explicitly embedded user-centered design processes by engaging end users throughout all stages of development and applying specific user-centered design mechanisms such as user surveys, context-of-use, iterative prototyping, and user testing[10]. Feedback loops were also used across phases to refine visualizations and improve overall usability[10]. Developers prototyped and tested seasonal forecasts and visualizations, iterating on symbols, parameters, and maps to improve usefulness and intuitiveness for users[10]. Project Ukko demonstrates how integrating user-centered design can enhance co-production by providing concrete mechanisms to synthesize user

input, clarify user requirements, and evaluate usability[10]. The project's outcomes, including more intuitive data communication, improved usability, and higher user engagement, underscore the value that user-centered design can add to co-production-based product development processes[10]. Viewed through the integration framework, this example highlights how the developers purposefully implemented an integrated user-centered design by building familiarity with its mechanisms and practices, mapping their co-production process, assessing constraints, and clarifying intended outcomes.

The SCA Tool is a land conservation and resilience decision-support platform for conservation professionals that illustrates implicit, selective integration of user-centered design within a co-production process[7, 49]. Although the project did not explicitly reference user-centered design, it incorporated several mechanisms and practices that align closely with user-centered design. Developed using a co-production approach, the SCA Tool emphasized bidirectional knowledge exchange between developers and users and an iterative development cycle[7]. Through a series of charrettes (design workshops), developers collaborated with users to establish shared priorities, gather feedback, refine features and metrics, and test functionality[7]. This product development approach centered on joint knowledge creation, problem-solving, and co-development and resulted in the launch of an assortment of geospatial products and use case studies[7, 49]. Throughout the process and charrettes, the developers gathered hundreds of user priorities, comments, and suggestions through mechanisms such as formally specifying user requirements, rapid prototyping, frequent user testing, and structured usability evaluation[2, 7, 8, 39, 50]. Although not labeled as user-centered design, these mechanisms are more typical of user-centered design than co-production and helped align the SCA Tool with user needs[2, 8, 39, 50]. The implicit user-centered design mechanisms were especially instrumental in ensuring that the data presented in the geospatial products was relevant to users' decision-making contexts[7]. This example shows how user-centered design mechanisms can emerge organically and be selectively integrated into co-production in digital or software-based product development. It also suggests that more explicit, intentional user-centered design integration could further strengthen the SCA Tool's usefulness, usability, and impact. Viewed through the integration framework, the developers could have more explicitly incorporated user-centered design by first deepening their familiarity with user-centered design and clarifying how it could support their desired outcomes. With this foundation, they would have been better positioned to determine which user-centered design mechanisms to selectively apply at different stages of their process.

Conclusion

A co-production approach to developing user-driven climate adaptation products that are salient, legitimate, and credible can be further strengthened with the integration of user-centered design. By employing either a selective or holistic integration, guided by an integration framework, user-centered design expands the possibilities and configurability of co-production by offering additional processes, mechanisms, and practices for developers. For developers new to co-production or focused on creating digital or software-based climate adaptation products, this Analysis offers a conceptual grounding in the

processes, mechanisms, and practices associated with co-production approaches to product development and user-centered design.

Although integrating user-centered design within co-production offers considerable potential, some open questions and limitations remain. Systematic literature reviews, while valuable for structuring and synthesizing knowledge, face study design and methodological constraints. In this review, we encountered interpretive challenges from the broad and interdisciplinary nature of co-production and human-computer interaction, variability in findings, and the risk of publication bias. Beyond methodological issues, practical constraints such as limited resources and time can restrict the ability to implement comprehensive product development approaches or sustain ongoing iteration, collaboration, and maintenance[6]. Especially given the critical nature of climate change and the need for timely climate adaptation products, extended product development cycles or delays in product delivery can reduce the relevance and utility of even well-designed, user-focused products[4, 5, 18, 19]. Finally, questions remain about scalability and generalizability, particularly how well tailored products can transfer across different settings. These limitations are explored further in the Methods, along with details on how an integrated approach to product development, combining user-centered design and co-production, can proactively address these hurdles during the development process and help manage them over time.

With these gaps and opportunities in mind, we explore how bridging the fields of climate services and human-computer interaction, and leveraging their respective co-production and user-centered design approaches, can drive innovation in how we build user-driven climate adaptation products. Ultimately, by prioritizing user collaboration throughout the product development process, we can ensure that climate adaptation products not only deliver their intended impact but also fully realize their potential to address climate adaptation challenges.

Methods

Here we describe our methods for mapping co-production and user-centered design in climate adaptation product development, focusing on processes, mechanisms, and best practices. We also provide background and review on climate services, user needs, human-computer interaction, and user-centered design.

We conducted a systematic review of journal articles and white papers using five databases spanning climate services and human-computer interaction: ScienceDirect, ACM Digital Library, IEEE Xplore, Climate-ADAPT, and the International Organization for Standardization (ISO). Searches were run July 25-26, 2023 across available database fields, including titles, abstracts, and full text, using terms targeting digital or software-based climate adaptation products.

For the co-production portion of the review, we used the following syntax, modified for each database's search interface:

- (“climate service” OR “climate information service” OR “climate change service”) AND (adapt!) AND (software OR digital OR tech! OR web! OR app!)

For the user-centered design portion of the review, few studies addressed climate products, so we expanded the search on July 26, 2023 to include environmental and sustainability-themed products. The following syntax was modified for each database’s search interface:

- (“human computer interaction” OR “hci”) AND (“user centered design” OR “ucd”) AND (“climate” OR “sustainab!” OR “environmental”)

The search targeted articles published starting on January 1, 2005, with no defined end date. However, given the timing of the searches, the effective end date was July 26, 2023. We used the databases listed below with structured, reproducible queries, applying consistent search strings across platforms and across both review portions, except for the ISO database. Database-specific ranking and sorting settings:

- **ScienceDirect:** Advanced search used with the specified strings; results sorted by relevance (ranked by how closely records matched the search terms).
- **ACM Digital Library:** Advanced search used with the specified strings; results sorted by recency (ranked by relevance with an additional penalty for older publications).
- **IEEE Xplore:** Advanced search used with the specified strings; results sorted by relevance (ranked by how closely records matched the search terms).
- **Climate-ADAPT:** Resource Catalogue search used with the specified strings; results sorted by relevance (ranked by how closely records matched the search terms).
- **ISO:**Advanced search used; initial queries returned no results, so queries were broadened to identify relevant standards. The platform does not specify ranking criteria and does not allow sorting. Modified queries included:
    - (climate service OR climate information service OR climate change service) OR (climate adapt)
    - (human computer interaction OR hci) OR (user centered design OR ucd)

After retrieval, abstracts were initially screened against inclusion criteria. The inclusion criteria were specifically designed as an initial quality filter, prioritizing studies of high relevance. Following this initial screening, duplicates were removed, and a secondary screening was conducted. During the secondary screening, each paper’s full text was read and reviewed against the inclusion criteria to ensure relevance, quality, and methodological rigor. Papers that were challenging to assess against the inclusion criteria were re-evaluated and assessed collaboratively with another author. Search syntax, screening methodology, and inclusion criteria were reviewed by all authors. For the co-production portion, we applied the following inclusion criteria:

1. Paper is focused on one or multiple of the following themes:

- Building climate adaptation products
- Lessons in or best practices for building climate adaptation products
- User needs for climate adaptation products

2. Paper mentions digital or software-based technologies
3. Paper is published in or after 2005
4. Paper is in English

For the user-centered design portion, we applied the following inclusion criteria:

1. Paper is focused on one or multiple of the following themes:

    - Building climate, sustainability, or environmental products
    - User-centered design mechanisms
    - Lessons in or best practices for user-centered design

2. Paper mentions digital or software-based technologies
3. Paper is published in or after 2005
4. Paper is in English

Following this process, 45 papers remained in the final database for the co-production portion of the review, published between 2016 and 2023 (inclusive) (Extended Data Table 5). In contrast, 35 papers remained in the final database for the user-centered design portion, published between 2005 and 2023 (inclusive) (Extended Data Table 6). The literature search and screening process is summarized in a flow diagram (Methods Fig. 1).

[**Methods Fig. 1 | Flow diagram of study identification, screening and inclusion**]

Coding and analysis

From the final 80 papers, we selected representative co-production and user-centered design processes based on design quality, stage clarity, and consistency with the broader literature. We then examined the papers for (1) mechanisms used in climate product development and (2) practices that contributed to, or were reported as supporting, product or process success. Similar mechanisms and practices were grouped within each corpus and mapped to the relevant stages of the selected co-production or user-centered design process (for full lists of mechanisms and practices, see Extended Data Tables 1-4).

In this review, we apply “mechanism” and “practice” broadly to capture as many elements as possible that were used, relevant, or considered useful for climate adaptation product development. This inclusive framing reflects the diversity found in the literature, where mechanisms and best practices are not always consistently labeled or defined but are nonetheless integral to product development processes.

“Mechanism” refers to the structured means by which product development is carried out. For further clarity, mechanisms can be distinguished between three types: artifact (for example, affinity diagram), activity (for example, interview), or actor (for example, knowledge broker). An “artifact” is a tangible output or tool that guides or results from the product development process. An “activity” is a structured engagement or procedure used to gather insights or test ideas. An “actor” is a person or group who participates in or supports the process. All mechanisms are categorized into one of these three types (for more details, see Extended Data). This typology is intended as a practical categorization to aid interpretation, recognizing that in practice the boundaries between these three types of mechanisms are often fuzzy rather than rigid.

“Practice” refers to any recurring activity, behavior, or procedural action that contributes to or supports product development. Practices range from high-level process elements (for example, defining roles) to applied and operational actions (for example, developing multiple prototypes). This broad categorization reflects the practical and conceptual variety of strategies used in the development of climate adaptation products.

Limitations

Several limitations shape the findings of this review. In study design and methodology, we faced interpretive challenges, and some differences between co-production and user-centered design may reflect terminology rather than fundamental distinctions. Given the interdisciplinary nature of human-computer interaction and the flexible, case-specific application of co-production, comparable mechanisms and practices may be described differently across fields. For example, workshops, interviews, user assessments, and prototyping techniques may be labeled differently in climate services versus human-computer interaction literature. This creates interpretive challenges and suggests that apparent differences between co-production and user-centered design may be smaller than they seem. Although our goal was to capture a wide range of mechanisms and practices as a developer-facing reference, this breadth is a limitation and warrants further clarification. Even so, user-centered design offers tested mechanisms that can strengthen climate adaptation product development, particularly for digital and software-based products. For example, user-centered design includes mature, widely used mechanisms that can support a more structured and rigorous product development process, such as context-of-use, user requirements specification, user testing, and usability metrics. These kinds of mechanisms could offer a way to introduce methodological diversity, practicality, and structure into co-production processes, potentially helping to translate user needs into more testable, design-oriented outputs.

Additionally, study findings may vary due to search timing, inclusion criteria, and the human screening and mapping process. These factors could introduce heterogeneity, as different reviewers might interpret the inclusion criteria or classify mechanisms and practices in varying ways. However, we identified these potential sources of variation during the review process and consulted additional researchers to validate both the approach and the quality of the findings.

Another methodological limitation is potential publication bias, as the peer-reviewed literature skews toward studies with positive results. To mitigate publication bias and diversify sources, we included Climate-ADAPT and ISO white papers alongside peer-reviewed studies. Finally, limiting searches to five databases may have missed relevant academic or grey literature, potentially omitting additional processes, mechanisms, practices, or cases.

There are also practical limitations of pursuing an integrated approach to product development as well. For instance, determining the minimum requirements for developing a user-driven climate adaptation product can be challenging, as necessary processes, mechanisms, and practices depend on the context. Similarly, funding or time constraints can limit the ability to implement an extensive product development approach. Time- and budget-planning across product development stages, paired with lower-cost engagement mechanisms (for example, remote interactions) and time-bound goals, can help mitigate these constraints[5, 18, 51]. To maintain co-production and user-centered design benefits while accelerating timelines, agile, modular approaches can gather feedback quickly and deliver functional prototypes earlier[16, 36, 52]. In particularly time-sensitive contexts such as disaster preparedness or narrow policy windows, prioritizing climate adaptation products that are delivered quickly and are “good enough” may be more effective than pursuing more refined but time-intensive tools. In the long run, user-driven product development may even save time by using early prototyping and testing to ensure products are usable and successful from launch[50].

These constraints also intersect with questions of scalability and generalizability. While many user-driven climate adaptation products are designed for specific user contexts, it remains an open question how well these tailored solutions can scale or transfer across different settings. However, integrating user-centered design into co-production may generate reusable approaches, design insights, or templates that support extension to new or adjacent contexts. User-centered design mechanisms such as context-of-use documentation and user requirements specifications can facilitate this process by providing structured insights into the original product’s user group, decision environment, and contextual conditions, forming a basis for modifying the product to other settings[39].

Climate services background

Climate services encompass the development and dissemination of climate adaptation products and other climate-related tools. Since emerging a few decades ago, the field has grown through initiatives such as the World Meteorological Organization’s Global Framework for Climate Services (GFCS), national climate services centers, and promotion by organizations including the European Union[13, 14, 29].

Although definitions and terminology vary, climate services generally refer to the use and tailoring of climate information to support decision-making on adaptation, mitigation, and other climate-related topics[1, 2, 19, 30, 53, 54]. Climate services are often framed as the production, translation, and transfer of climate information, with an emphasis on usable, actionable, and tailored information for decision-makers[11, 25].

For climate adaptation products, in particular, the information the products contain, use, or deliver can include shorter-term weather data, longer-term climate data, physical measurements, climate impact variables, expert advice, and more[2, 25, 43]. Climate adaptation products can also span timescales from sub-seasonal to decadal and delivery mediums from fully digital and software-based products to non-digital formats[3]. These products can support decisions in areas such as climate risk and impact assessment, planning and infrastructure, and resource management[16, 55-57].

Despite their intent, climate adaptation products often fall short of practical user needs and the urgency of current climate risks[29, 44]. Many products fail to deliver timely, decision-relevant insights, limiting their value for adaptation action[5, 23, 29]. As warming thresholds are surpassed, there is a growing need for product development approaches that help users interpret diverse climate information and support long-term as well as immediate and near-term adaptation decisions[1, 12, 19, 20, 23, 54].

User needs background

Meeting user needs for climate adaptation requires addressing numerous aspects. There is the aspect of uncertainty in future climate conditions and the need for scientific expertise to interpret projections and results, alongside the need to understand adaptive capacity across organizational and governance scales[1, 13, 19, 58]. There is the breadth of short- and long-term adaptation options and how they interact with broader societal and environmental dynamics[56, 57]. There is the need to understand user context and the challenge of navigating multi-stakeholder decision-making with competing interests[13, 28]. And there is the need for timely delivery to support decisions under urgent or rapidly evolving climate conditions[4, 5].

To surmount these complexities and build efficacious climate adaptation products, the climate services literature typically emphasizes core tenets of salience (relevance), credibility (quality and dependability), and legitimacy (impartiality and fairness)[5, 8, 19, 30, 43, 58-60].

Salience underscores that one-size-fits-all, supply-driven information is often ineffective because user groups need different types of information[42]. For climate adaptation products, this means tailoring information and delivery to ensure it is relevant to the decisions it will inform[41]. Salience can also involve adjusting spatial and temporal scales to fit decision context, using clear prose or visuals, tailoring the level of detail to help users absorb information, linking information to local contexts through customized metrics, and using stories that resonate with users' livelihoods[42, 61-65].

Credibility centers on information quality and whether users trust a product's results[8, 42]. For climate adaptation products using weather forecasts or climate projections, credibility depends on clearly communicating uncertainty so users' expectations for future scenarios are aligned with what the information can support[8, 63]. Credibility can also involve using trusted data sources, documenting

assumptions and methods, adhering to data and metadata standards, implementing quality assurance, and tailoring communication about confidence and uncertainty[3, 25, 26, 43, 62].

Legitimacy involves aligning with users' standards, values, and norms and maintaining transparency in the process[8, 26, 63]. For climate adaptation products, legitimacy depends on respecting user views and feedback to build mutual trust between developers and users[36, 63]. Legitimacy can also involve adhering to national and global standards, incorporating feedback, tracing results to reliable sources, following agreed work plans, aligning with local knowledge and values, and communicating transparently[8, 25, 26, 44, 63, 66]. Salience, credibility, and legitimacy are interconnected and rely on sustained dialogue and collaboration between developers and users[42]. These criteria provide a benchmark for how to pursue a demand-driven model for climate adaptation product development and build products that are more likely to meet users' needs, be used by decision-makers, and influence adaptation action[3].

Co-production background

Climate services literature often advocates for co-production, a wide-ranging theory of research engagement, interaction, and collaboration, to build salient, credible, and legitimate products and help close the usability gap[5, 6, 18, 29, 31, 34, 36, 64]. Co-production is typically described as the integration of diverse knowledge, experiences, and practices to foster mutual learning and develop new ideas, products, processes, or outcomes[6, 67, 68]. It often integrates participatory approaches, including related 'co-' terms such as co-design and co-development[6, 29, 31, 34, 61, 64, 69].

Co-production spans disciplines beyond climate services, with roots in participatory development, public services administration, and science, technology, and policy, and is conceptualized differently across fields[5, 18]. Even within climate services, co-production lacks a standardized approach[13, 16, 29, 30]. While recent discussions have explored the potential for greater standardization in the development and delivery of climate services[30], co-production is still widely understood as a guiding framework that is case-dependent and shaped by the specific purpose, users, and decision-making environment[5, 13, 16, 29, 31, 34, 36].

Human-computer interaction background

Human-computer interaction emerged in the 1980s to improve the interface between users and computers[33]. The interdisciplinary field aims to design systems that improve interactions among users, tasks, tools, and environments[70]. To guide this aim, human-computer interaction draws on psychology, emphasizing user cognition, perception, mental models, and attention[50]. In summary, human-computer interaction strives to build usable products and positive user experiences, often through usability principles and user-centered design[33, 50].

Usability is the degree to which a user can utilize a product to meet specified goals within a particular context[71]. The theory reflects how well users can achieve goals with effectiveness (goals achieved completely and accurately), efficiency (goals achieved in a timely manner), and satisfaction (goals achieved with comfort and positive emotions)[32, 39, 71, 72]. More recently, usability has expanded to include learnability, accessibility, maintainability, recognizability, and operability[33, 71]. User-centered design is frequently cited in human-computer interaction as an approach that can improve and help realize usability[32, 46, 73]. In fact, usability is a core criterion for evaluating the success of a user-centered design process[38].

User-centered design background

User-centered design, often referred to as human-centered design, is a design approach and methodology focused on developing products that meet user needs[32, 38, 39]. It can be viewed as a framework, craft, or philosophy, but regardless of its classification, user-centered design emphasizes placing users at the center of the product development process and understanding their characteristics, needs, wants, and limitations[8, 45]. Key principles of this approach include ideation, prototyping, iteration, validation, usability, utility, and verification[32, 39, 50, 73, 74]. Given its foundation in usability and user experience, user-centered design is widely applied in developing websites, software applications, and other digital or software-based products[32, 75, 76]. Similar to co-production approaches to product development, user-centered design emphasizes user interaction and aims to build products that are useful, usable, and used[10, 50].

Although user-centered design is well established in human-computer interaction and aligns with co-production principles, it is one of several user-engagement traditions in the field[77, 78]. Other approaches such as participatory design, co-design, critical design, and design and emotion reflect different conceptualizations of the developer-user relationship and offer alternative frameworks for user involvement[77, 78]. We focus on user-centered design because it is methodologically mature, stage-structured, and centered on usability and iteration, closely paralleling co-production and offering an accessible entry point for developers less familiar with human-computer interaction[2, 38, 73, 75, 78]. At the same time, critiques of user-centered design also note how it can position users too passively or narrowly[78, 79]. In sustainable human-computer interaction, which applies a critical environmental lens to product and systems design, some argue that user-centered design's human-centeredness can overlook ecological systems and non-human actors[79-82]. Given our focus on digital and software-based climate adaptation products, user-centered design offers a pragmatic, well-documented foundation for integration, while future work can examine how other human-computer interaction approaches, particularly sustainability-oriented ones, might further extend these processes.

Declarations

The authors declare no competing interests.

Data availability

This study is a systematic review of published literature. All data supporting the findings of this review are publicly available in those sources, which are described in the Methods and listed in the Extended Data.

Acknowledgements

We would like to thank Nancy Freitas, Kripa Jagannathan, and Brian L. Trelstad for their valuable review and feedback on the ideas for this paper.

Author contributions

N.A.C. led the study, including the literature search and systematic review. N.A.C. conducted the searches, gathered articles, screened articles, and extracted and categorized mechanisms and best practices from articles, with additional review and support from A.D.J. All co-authors reviewed the final results. N.A.C. drafted the manuscript, and all co-authors contributed to reviewing, commenting on, and revising the text.

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Tables

Table 1 | Co-production stages for product development

Stage	Definition
Identify Actors & Build Partnerships	Recognize and gather stakeholders from multiple disciplines
Co-Explore Need	Understand decision need and decisions that product can address
Co-Develop Solution	Build product in collaboration with stakeholders
Co-Deliver Solution	Distribute product to stakeholders
Evaluate	Test and refine product with stakeholders

Notes: Stage definitions draw on the Vincent et al. (2018) co-production approach[5].

Table 2 | User-centered design stages

Stage	Definition
Plan Process	Prepare project for user involvement
Understand Context	Identify the users, user needs, and user preferences and behaviors
Specify User Requirements	Identify and define user, business, and organizational goals
Produce Solutions	Build initial to final products based on user needs and requirements
Evaluate Solutions	Test products with users and get feedback

Notes: Stage definitions draw on the ISO user-centered design approach[39].

Figures

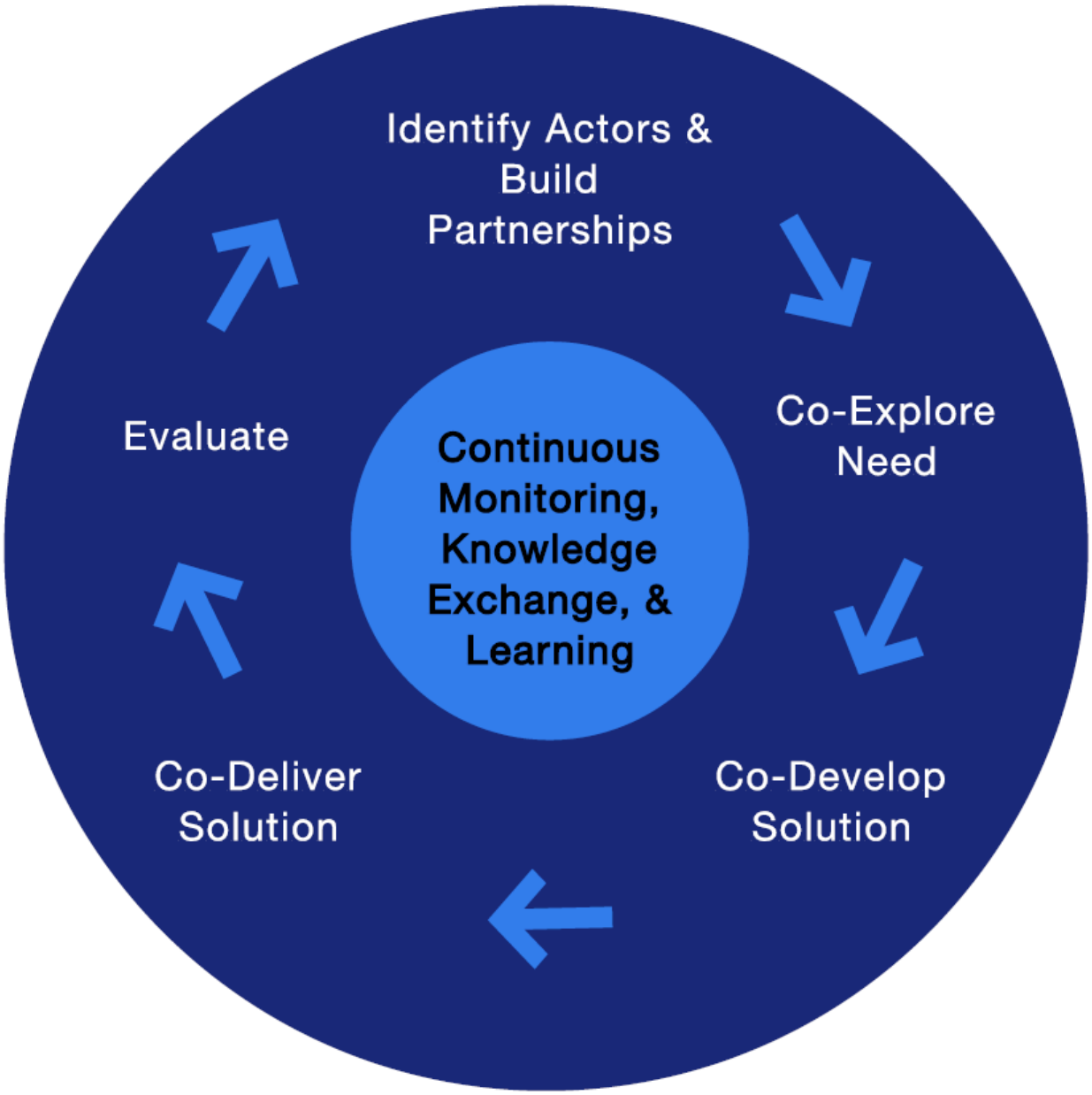

Figure 1

Co-production process for product development. Diagram of a five-stage co-production process for product development. The cycle proceeds through *Identify Actors & Build Partnerships*, *Co-Explore Need*, *Co-Develop Solution*, *Co-Deliver Solution*, and *Evaluate*, and is organized around an inner loop of continuous knowledge exchange, monitoring, and learning[5]. The process is guided by the principles of inclusiveness, collaboration, and flexibility, and the resulting product is shaped by three principles: decision-driven, process-based, and time-managed[5].

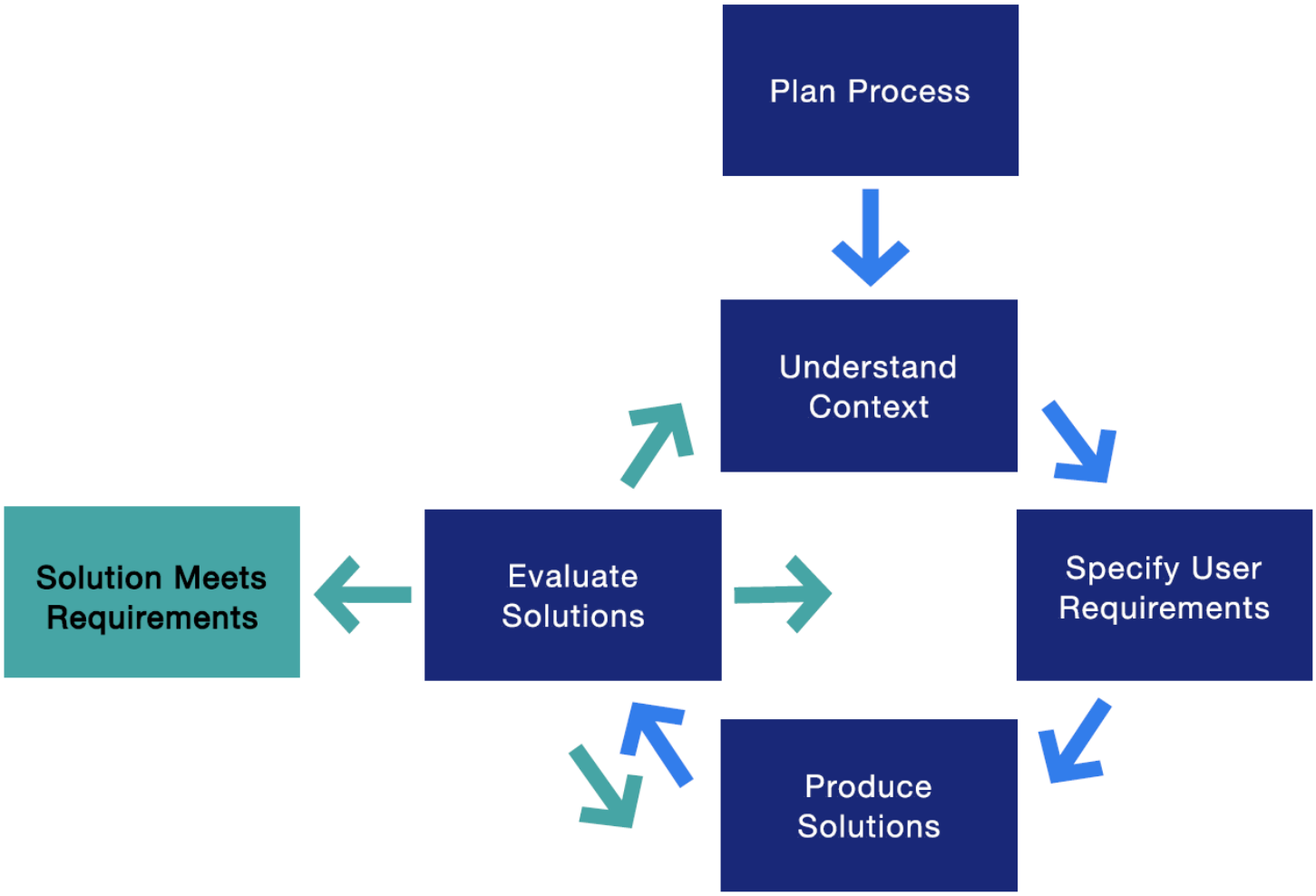

Figure 2

User-centered design process. Diagram of a five-stage user-centered design process. The cycle iterates through *Plan Process*, *Understand Context*, *Specify User Requirements*, *Produce Solutions*, and *Evaluate Solutions*, with evaluation outcomes informing returns to earlier stages when requirements are not met[39]. The process is guided by principles that emphasize an explicit understanding of users, tasks, and environments; continuous user involvement; evaluation-driven refinement; iteration; attention to the full user experience; and multidisciplinary design teams[39].

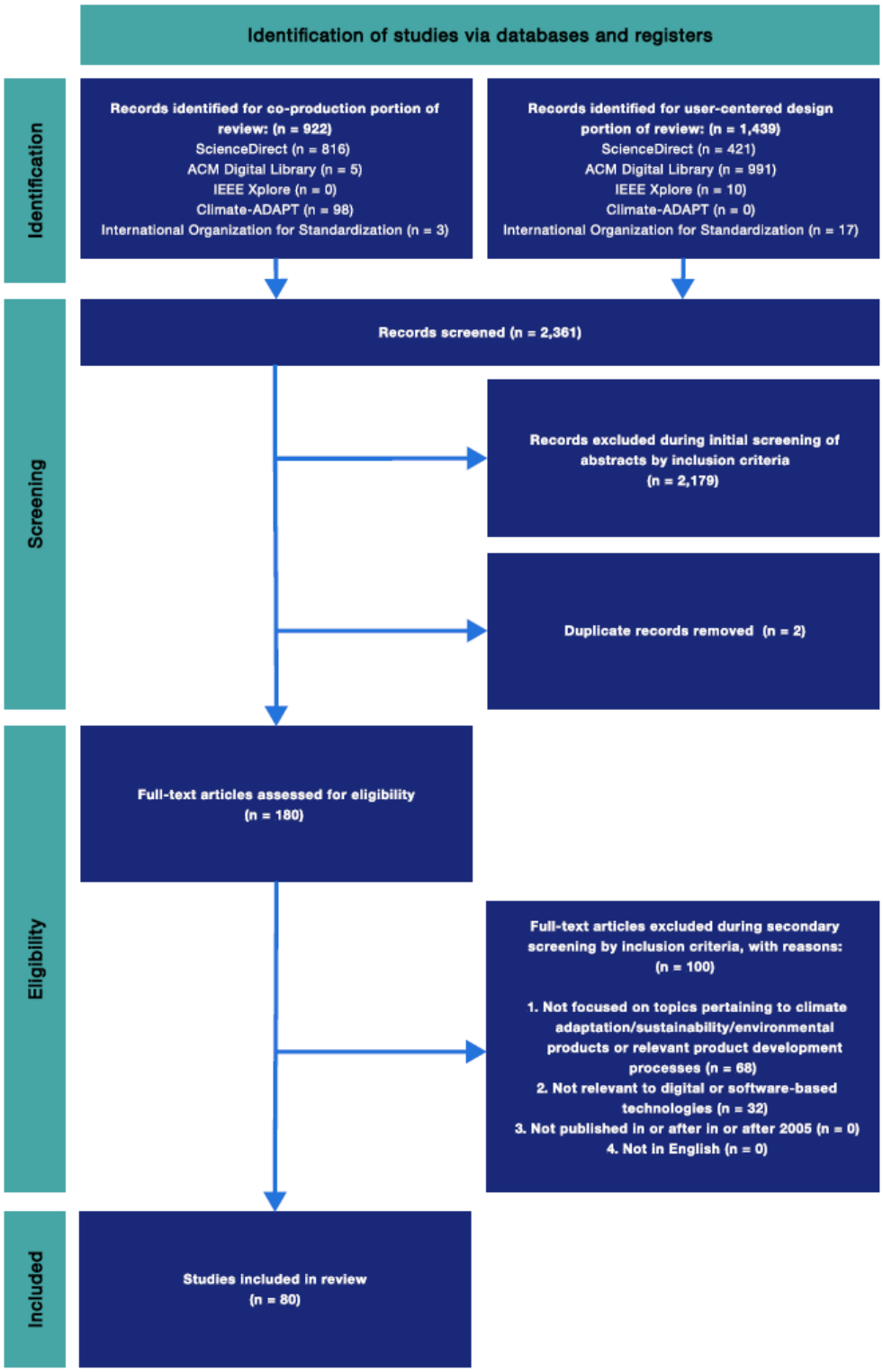

Figure 3

Methods Fig. 1 | Flow diagram of study identification, screening and inclusion. Flow diagram of the systematic review based on PRISMA guidelines. Records were identified across five databases (ScienceDirect, ACM Digital Library, IEEE Xplore, Climate-ADAPT, and the ISO) for the co-production (n = 922) and user-centered design (n = 1,439) searches and subsequently screened (n = 2,361). Records were excluded during abstract screening (n = 2,179) and duplicates removed (n = 2) prior to full-text

eligibility assessment (n = 180). Full-text exclusions (n = 100) were due to lack of topical focus (n = 68) or lack of relevance to digital or software-based technologies (n = 32). A total of 80 studies were included in the final review.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Extendeddatatables.docx