CENTERING KNOWLEDGE CO-PRODUCTION IN SUSTAINABILITY SCIENCE

WHY, HOW, AND WHEN

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ABSTRACT. Solving complex sustainability problems requires novel, creative approaches. One such approach is knowledge co-production, where individuals with diverse expertise collaborate to generate knowledge in support of transformative solutions. Although the concept is not new, there is growing interest in using knowledge co-production in sustainability science, yet relatively few resources offer a practical guide, rooted in theory, to help researchers and practitioners understand when and how to co-produce in the context of sustainability science. This paper synthesizes the existing literature across multiple disciplines to present a novel framework and actionable strategies for effective knowledge co-production in sustainability. The wheel of knowledge co-production, the conceptual framework presented, emphasizes the importance of iterative phases of building relationships, assessing available resources, involving diverse participants, considering context, and working together with partners to design mutually beneficial and respectful processes and outcomes.

INTRODUCTION

Solutions are urgently needed for the complex challenges facing our social-ecological systems. These "wicked" problems demand innovative and unique approaches to create solutions that benefit both human and natural communities—the foundation of sustainability science (Clark and Dickson, 2003). The process of knowledge co-production has gained increasing attention for generating policy-relevant, solutions-oriented, and socially robust knowledge, and is one of the key concepts consistently discussed as the most effective strategy for mobilizing knowledge in the context of evidence-informed policy and practice (Bandola-Gill et al., 2023).

Knowledge co-production has been widely practiced in the public health field for decades and more recently has been adopted as one of the most important concepts in research and practice for global sustainability (Miller and Wyborn, 2020). Knowledge co-production and related concepts have many definitions and may mean different things to different actors in different contexts (Wyborn et al., 2019; Bandola-Gill et al., 2023; Table 1). We define knowledge co-production for sustainability as an interactive, participatory process that brings together diverse actors such as scientists, practitioners, and community members to collectively generate, integrate, and apply knowledge to address complex sustainability challenges.

This approach extends beyond a single epistemology (e.g., Western scientific methods) and embraces diverse forms of knowledge generation, such as traditional, Indigenous, and local knowledge (Dixon, 2016). It incorporates interdisciplinary perspectives, those that exist across different life experiences and occupations, and those that are fundamentally connected to place (Ardoin et al., in press). Collaboration and knowledge co-production with societal actors, such as decision-makers and local community members, are particularly important for projects where concrete societal change and implementation of solutions is a main objective, as these individuals are often the most closely engaged with or impacted by the scientific question or issue at hand (Bandola-Gill et al., 2023). The benefits of knowledge co-production include: better quality of research and conceptualization of complex systems; strengthening ownership and buy-in; building public trust in evidence-based decision-making; stronger inclusion and equitable knowledge generation; and strengthening innovation, implementation, and overall success of sustainability initiatives (Wyborn et al., 2019).

The sustainability field's eager uptake of knowledge co-production approaches is reflected in its proliferation in related literature, governance venues, and funding requirements (Arnott et al., 2020b; Norström et al., 2020; Vaughn and Jacquez, 2020). Some knowledge co-production frameworks and practical guides exist in

related domains, such as in the context of urban and mental health (Roper et al., 2018; Audia et al., 2021); food, energy, and water systems (Kliskey et al., 2021); fisheries research (Cooke et al., 2020); early career professionals in ocean sustainability (Satterthwaite et al., 2022); Indigenous Peoples in Arctic research (Ellam Yua et al., 2022); co-design (Moser, 2016); and actionable science (Beier et al., 2017). Additionally, principles have been described for knowledge co-production in sustainability research (Norström et al., 2020). Yet, relatively few resources offer a framework and practical guidance related to knowledge co-production in sustainability science, such as assessing when knowledge co-production is appropriate and how to navigate the process based on available resources (e.g., time, funding, relationships) and project partners' values.

The goals of this paper are to provide: (1) a novel and synthetic framework with concrete phases, key questions, strategies, and crosscutting themes for engaging in knowledge co-production for sustainability; (2) examples that illustrate how the process has worked in practice; and (3) recommendations for further advancing diverse participation in knowledge co-production for sustainability.

METHODS

This paper synthesizes the existing literature across different fields and combines the narrative review with lessons from practical experiences to provide an applicable, overarching framework for knowledge co-production in the context of social-ecological sustainability. We use the term "coastal communities" to refer to people across communities of place, practice, identity, and interest with connections to any coastal and marine habitat, including estuaries, nearshore coastal regions, open ocean habitats, and the Great Lakes. We use the terms "participants," "interested parties," and "community members/partners" to encompass the broad range of actors interested in and/or affected by a process, including but not limited to those who have a stake, share, right, or interest in a particular question or issue. Thus, we explicitly choose to not use the term stakeholder to be more inclusive of the various types of actors engaged in knowledge co-production and as a step toward decolonizing language used in research (following Reed and Rudman, 2023).

The framework is a product of synthesizing existing literature from structured searches (e.g., Google Scholar) using terms related to "knowledge co-production" (Table 1) and supplemented with literature contributed by the authors. It has been co-designed by the authors through an iterative process of reading, synthesizing, discussing, and writing. Practical insights are drawn from the authors, who collectively bring experience as natural and social scientists and Sea Grant personnel working at the interface of scientific research, policy, and

TABLE 1. Common terminology for knowledge co-production and participatory approaches for sustainability.

TERM	DEFINITION	CITATION	EXAMPLE RELATED TERMS
Knowledge Co-Production	An interactive, participatory process that brings together diverse actors such as scientists, practitioners, and community members to collectively generate, integrate, and apply knowledge to jointly create actionable insights and solutions.	Adapted from Wyborn et al., 2019	Participatory Design, Co-Operative Inquiry, Collaborative Research, Community Engagement, Engaged Scholarship, Tribally-Driven Participatory Research, Co-Approaches
Knowledge Exchange	Processes that generate, share and/or use knowledge through various methods appropriate to the context, purpose, and participants involved.	Fazey et al., 2013	Collaborative Learning
Knowledge to Action & Knowledge Translation	An iterative, dynamic and complex process that concerns the creation and application (action cycle) of knowledge.	Straus et al., 2009	Actionable Knowledge; Research to Action (R2A); Science to Society; Translational Research; Integrated Knowledge Translation; Implementation Science; Research Utilization; Knowledge Mobilization
Community-Engaged Research	A research paradigm that creates spaces for communities, community members, and community-based organizations to work in collaborative partnerships with academic researchers. It aims to produce research outputs that benefit the community, while also meeting the rigors and standards expected from academic research.	Halvorsen et al., 2019	Community-Based Participatory Research; Community and Citizen Science (CCS); Participatory Action Research (PAR); Participatory Research/ Monitoring; Public Science
Sustainability Science	A problem- or solution-oriented science focused on the usefulness of the knowledge it produces, an applied science, an action-oriented science, and a transdisciplinary venture that achieves transformation through the deep involvement of stakeholders and relevant constituencies in the research process.	Nagatsu et al., 2020	Ecology/Human Ecology, Global Change Science, Ecological Economics, Complexity & Systems Science, Transdisciplinary Science

resource management in aquatic social-ecological systems. Geographically, the authors span ocean, coastal, and Great Lakes regions of the United States, work across local and regional contexts, and range in experience from early to late career. The professional experiences with and reflections on co-production are shaped by technical training as scientists; experience approaching this work from an evidence-based lens; and designing, leading, or facilitating these processes. Nevertheless, it is important to acknowledge that the authors represent just a fraction of those involved in co-production processes. This limitation underscores the opportunity for further inclusive development of the framework, potentially through co-production with community members, planners, managers, and local and indigenous partners. The intention is to integrate theory with collective expertise from practical experience to promote critical thinking and ongoing discussions and to provide interested researchers and practitioners with the skills necessary to engage in knowledge co-production.

ADAPTIVE, ITERATIVE WHEEL OF KNOWLEDGE CO-PRODUCTION

Introduction to the Wheel

The wheel of knowledge co-production is a synthetic framework for implementing co-production approaches in sustainability sciences (Figure 1). The wheel consists of seven interconnected phases (inner circle; Figure 1a) and objectives within each phase (Figure 1b) that guide the knowledge co-production process with crosscutting, foundational themes woven throughout (outer circle; Figure 1a). Although presented in phases, it is a responsive, iterative, and adaptive process of equitable engagement that is nonlinear, may not proceed through all phases, and allows for continuous learning, relationship building, and adaptation throughout and beyond a single project. For simplicity, the foundational themes (denoted as *Themes* in text) have been described in a relevant phase; however, each of the foundational themes are considered essential to the process as a whole and are not bound within a particular phase. The wheel emphasizes the importance of building trust, understanding context, and co-designing with the community for meaningful and impactful outcomes. Key questions and strategies are included to help assess whether co-production is appropriate for the situation and how to successfully navigate a given phase (Figure 1; Box 1).

Relate Phase

The Relate Phase sets the foundation for collaboration, emphasizing trust, empathy, and effective communication (Figure 1; Boxes 1–3).

The process of co-production often begins by identifying the people or groups who share common interests or values regarding a place or topic of focus. The intent is to build and maintain relationships rooted in trust and collaboration, which requires early engagement in or prior to the co-production process, allowing nuanced understanding of one another, the situation, context, or place of focus and for the creation of shared goals. Sustained long-term engagement,

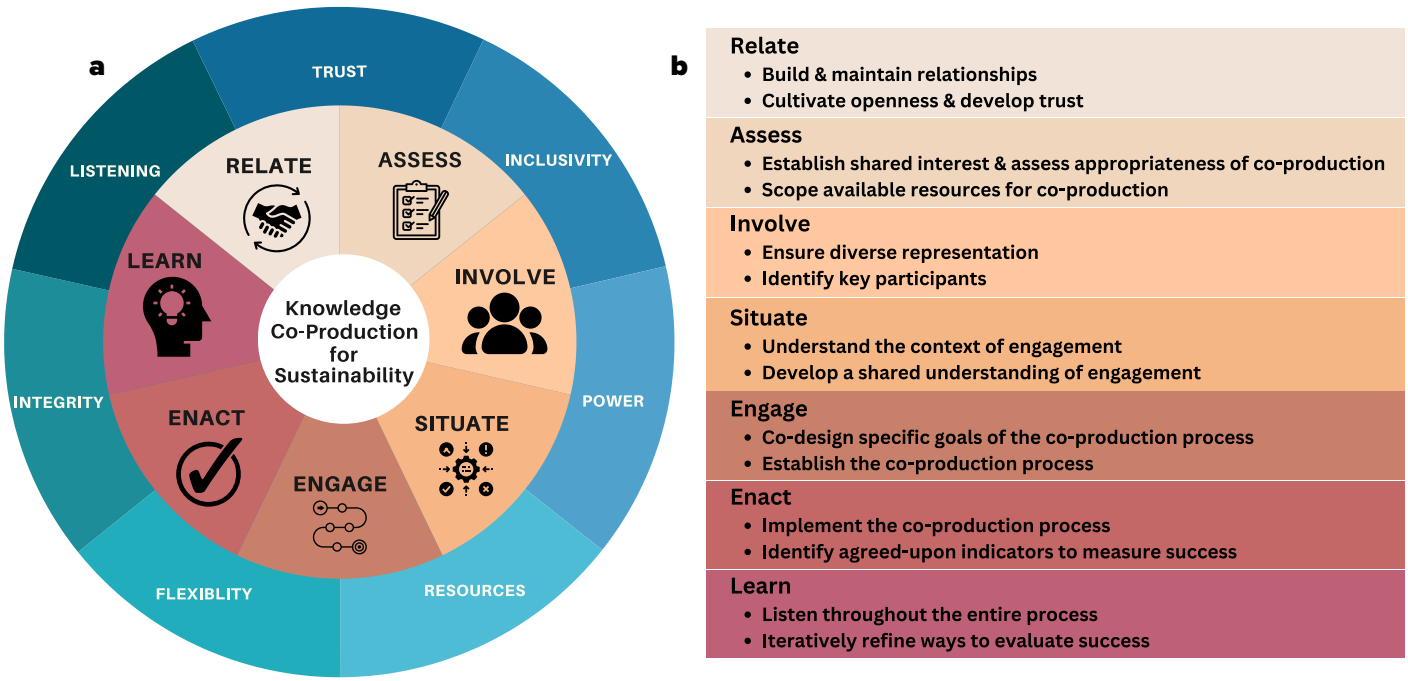

FIGURE 1. (a) Wheel of Knowledge Co-Production for Sustainability. There are seven phases (inner wheel; red shades) and foundational themes (outer wheel; blue shades). The seven phases are separate elements of a co-production process that may play out in sequence but in practice are more likely to be parts revisited non-sequentially. The process is nonlinear, iterative, and may occur over many cycles. The foundational themes include listening, trust, inclusivity, power, resources, flexibility, and integrity. (b) Corresponding summarized objectives are highlighted for each phase.

BOX 1. OBJECTIVES, EXAMPLE REFLECTIVE QUESTIONS, AND EXAMPLE STRATEGIES ASSOCIATED WITH EACH PHASE OF THE WHEEL OF KNOWLEDGE CO-PRODUCTION

RELATE

OBJECTIVES
- Build and maintain relationships
- Cultivate openness & skills/attitude for transdisciplinary relationship building
- Develop trust

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- What shared interests do I have with those around me? What issue/problem/questions/interests do we have in common?
- Who would I like to work with? Who should I be working with that I am not?
- How can I best listen to the needs of my fellow community members?
- How might I support and develop my transdisciplinary & co-production skills?

EXAMPLE STRATEGIES
- Meet-ups, events, and networking opportunities (e.g., centered on things like shared interests, sharing food, having fun, storytelling)
- Mentorship opportunities
- Participate as a co-learner
- Partner with bridging organizations and community-based organizations
- Participate in trainings for co-approaches/transdisciplinary research

SOURCES
- Moser, 2016; Roux et al., 2017; Davies et al., 2020; Ness and Wahl, 2022; Satterthwaite et al., 2022

ASSESS

OBJECTIVES
- Establish shared interest
- Scope context and available resources
- Understand if co-production approaches are needed, possible, and appropriate given context

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- What or who is motivating engaging in co-production? Is co-production appropriate and possible in this context?
- Are the social, institutional/ governance, and power structures of the system participants are working in conducive to knowledge co-production efforts?
- What information already exists from previous formal or informal needs assessments?
- What resources are available for the knowledge co-production process? Are there other resources that we haven't thought about?

EXAMPLE STRATEGIES
- Observations in settings where participants engage and interact
- Interviews and informal conversations with key participants to understand interests
- Listening sessions
- Resource analysis
- Systems scoping exercises (see Schlüter et al., 2021, for specific tools)

SOURCES
- Reed et al., 2009; Muñoz-Erickson et al., 2017; Djenontin and Meadow, 2018; Roper et al., 2018; Bamzai-Dodson et al., 2021; BARHII, 2021; Leventon et al., 2021; Schlüter et al., 2021; Satterthwaite et al., 2022; Cooper et al., 2023

INVOLVE

OBJECTIVES
- Scope the community
- Identify interested parties
- Investigate relationships between actors
- Include diversity of viewpoints, interests, and constraints in the social-ecological system

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- Who should be involved in the process? Which people and forms of knowledge shape the project?
- Have we got the right people in the group? Who is not represented but should be represented? Do we have a diversity of expertise across axes such as disciplines, sectors, backgrounds/lived experiences, locations, knowledge systems? Who can or cannot participate and why (e.g., access to information, decision-making spaces, and resources to participate)?
- What actors are perceived as credible and legitimate, and why or why not?
- When there are conflicts between the goals of equity, diversity, and democracy, how should trade-offs, such as between direct public participation and indirect representation, be managed?

EXAMPLE STRATEGIES
- Brainstorm with people in your organization, officials, and others already involved in or informed about the effort and start listing categories and names
- Conduct analysis/mapping of key participants and interested parties
- Consult with organizations that either are or have been involved in similar efforts
- Get more ideas from stakeholders as you identify them (e.g., snowball sampling)

SOURCES
- Davies et al., 2020; Muñoz-Erickson et al., 2017; Schlüter et al., 2021; Akerlof et al., 2023; Center for Community Health and Development, n.d.

SITUATE

OBJECTIVES
- Understand context of engagement
- Understand complex social-ecological system dynamics & behavior
- Assess power, purpose, politics, pathways

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- What resources will we need to find before we go ahead? Are all partners appropriately trained, resourced, and supported? What might still be needed? What support should be in place for participants to ensure effective collaboration? Does anyone need more resources, support, or training to be able to participate fully? Are there limits to any partners' participation?
- In what ways does power manifest within our partnership? How can we identify and address power differentials within the group? What are the power dynamics, between participants or structural, that we need to attend to? How can power be redistributed within the partnership?
- How are participants knowledge systems structured and functioning? What other knowledge systems do partners already rely on to make their decisions? What epistemic practices inform participants visions and expectations of the issue?
- What constitutes participants networks?
- What does the social-ecological system look like that the issue sits within?
- Is there stress, pressure, conflict in the issue? How does this affect our work?

EXAMPLE STRATEGIES
- Conduct interviews & surveys
- Analyze and model complex social-ecological system (see Schlüter et al., 2021, for specific tools)

SOURCES
- Reed et al., 2009; Muñoz-Erickson et al., 2017; Roper et al., 2018; Davies et al., 2020; Chambers et al., 2021; Schlüter et al., 2021

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BOX 1. CONTINUED...

ENGAGE

OBJECTIVES
- Jointly define goals & objectives
- Establish level of ability and interest to engage
- Foster understanding & ownership of the process and outcomes by those involved

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- Do all participants have a solid understanding of co-production? What else might people need to support and deepen this understanding? When is it most important to use co-production in the project, as a whole or segments of the process? What potential challenges might arise in our co-production efforts?
- What are participants able to bring to the process and what motivates us? What are the incentives, goals, expectations of participants? What does success in outcomes & process look like to each participant?
- What will we do if people experience difficulties as a result of their involvement? What do we need to put in place to address these difficulties?
- How can we create a plan to address power dynamics throughout our co-production journey?
- How often do we need to meet, how and where? How will we communicate with each other? Do we have enough information about the work and what happens between meetings?
- How is work being allocated in the team? Are we making assumptions or is there discussion about who does what and the scope for people to take on different roles?
- How should decisions be made and by whom? What has already been decided and by whom? Are we all clear about what is decided and do we communicate this with anyone missing?
- What process should be followed if a participant leaves the group?

EXAMPLE STRATEGIES
- Use probing questions to define goals in an initial meeting (see questions in Beier et al. 2017)
- Offer many ways to engage & eliminate common barriers to participation (e.g., host events in safe or community spaces, offer stipends for participation and travel)
- Allow participation and engagement across the entire knowledge generation process

SOURCES
- Beier et al., 2017; Roper et al., 2018; Davies et al., 2020; BARHII, 2021

ENACT

OBJECTIVES
- Implement the co-designed process
- Establish initial metrics of "success"

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- Do participants understand why we are engaging in the process? Do we have a shared understanding of the problem/agenda and what we hope to do together?
- Are we providing many different ways to engage? Are we continuing to follow our agreed upon process? How do we structure and allow opportunities for checking in about the process and adapting as necessary?
- Do the tools and strategies we are using match our intended goals?
- What do users know about how the knowledge was generated in order to evaluate whether the knowledge expressed is credible, legitimate, and salient? How is uncertainty about the knowledge being communicated?
- Is there trust? How can we build trust among partners during initial interactions? How can we make our first interactions feel different from usual meetings?
- What level of specificity and recording should be captured during the co-production process, keeping in mind that some information could be sensitive and specific documentation could hinder level of engagement?

EXAMPLE STRATEGIES
- Participatory action research and participatory data collection (e.g., participatory mapping, ranking exercises, focus group discussions)
- Participatory modeling
- Future analysis (e.g., participatory scenario planning, road mapping, horizon scanning)
- Facilitated dialogues (e.g., world cafe, listening sessions)

SOURCES
- Muñoz-Erickson et al., 2017; Roper et al., 2018; Schlüter et al., 2021; Akerlof et al., 2023

LEARN

OBJECTIVES
- Implement knowledge co-production process
- Evaluate process and outcomes
- Provide opportunities for social learning & community reflection

EXAMPLE GUIDING/REFLECTIVE QUESTIONS
- What does success in outcomes & process look like to all parties involved in the co-production? What are the project outcomes and outputs, both intended and achieved? How are differences in priorities reconciled and compromised on?
- Is what we are doing co-production and how do we know? Is another word more appropriate?
- Have we facilitated a process where all partners have been able to identify their strengths and their needs?
- How can we continually maximize power- and capacity-sharing?

EXAMPLE STRATEGIES
- Create a logic model to identify project's theory of change
- Host community listening sessions
- Build off of other example outcome and process evaluations
- Tailor metrics of success for those included in the process
- Solicit and respond to feedback from all levels of the process

SOURCES
- Beier et al., 2017; Roper et al., 2018; Ardoin et al., 2022; Ness and Wahl, 2022; Sey and Rothschild, 2023

beyond grant cycles, is equally important to allow for the longer timescales often required to observe outcomes related to complex issues (Kliskey et al., 2021).

Humility is a cornerstone of authentic relationship building and is necessary for cultivating openness and developing trust (Liboiron, 2021). Trust plays a crucial role in knowledge co-production by fostering openness, transparency, and effective communication among interested parties (*Theme: Trust;* Norström et al., 2020). This leads to knowledge sharing, learning, and innovation, and increases the likelihood of honest collaboration, cooperation, and collective ownership of co-produced knowledge.

Assess Phase

The Assess Phase promotes reflection on the appropriateness of co-production methods in a given context (**Figure 1**; **Boxes 1–3**; Lemos et al., 2018).

It is important to establish shared interest and assess appropriateness of co-production. This includes considering *why* a co-production approach may be valuable to the challenge at hand, who has helped to shape the question(s) needing to be answered, and what is motivating the use of co-production approaches. Contextual factors are also important to consider, including pre-existing relationships and power dynamics among actors, or social norms that legitimize different forms of knowledge (Turnhout et al., 2020). A commitment to sharing *power* among partners is a vital piece of collaborative processes that can result in increased *trust* and genuine *inclusion* of partners' priorities (*Themes: Power, Trust, Inclusivity*), so it is important early on to agree upon the degree to which power and decision authority will be shared (Shirk et al., 2012).

Given mutual motivation to pursue a co-production approach, it is then critical to scope the available resources for co-production such as the time and capacity available (*Theme: Resources*). Co-production approaches require more time, funding, and specialized skill sets, such as facilitation and conflict mediation, as compared to less participatory approaches, and these resources must be identified and committed prior to beginning the co-production process (Beier et al., 2017).

Involve Phase

The Involve Phase is pluralistic and focuses on inclusivity, diversifying participation, and involving a wide range of people with varied perspectives and expertise (**Figure 1**; **Boxes 1–3**).

Successful knowledge co-production requires ensuring diverse representation (*Theme: Inclusivity*; Enengel et al., 2012). Participants coming from different personal and professional backgrounds and holding differing authorities are likely to bring different types of knowledge, understandings of the problem, interpretations, perspectives, methods, ideas for solutions, and norms of engagement, debate, and collaboration (Norström et al., 2020). On the one hand, this diversity can foster innovative and creative research and learning that benefits both the local and

BOX 2. AN EXAMPLE OF THE WHEEL OF KNOWLEDGE CO-PRODUCTION IN ACTION

RELATE

Through the synergistic interplay of supporting applied research with the sustained and timely delivery of that knowledge to stakeholders, Sea Grant has been at the forefront of conducting community-based, co-production of knowledge for over 50 years. When recent scientific findings revealed that DDT (dichlorodiphenyltrichloroethane) contamination extended to large areas of the Southern California Bight seafloor, it ignited public concern and interest in significant research investment. In response, the University of Southern California Sea Grant Program and the California Sea Grant Program (collectively "Sea Grant" in this example) co-led "A Deep Ocean DDT Research Needs Assessment for the Southern California Bight" (herein "Assessment") to assist funders and resource managers in identifying what new DDT research is most critically needed (Almada et al., 2023). Sea Grant initiated the Assessment at the encouragement of state and federal resource agency partners who saw the need for Sea Grant's strength as a neutral broker capable of accurately identifying and reflecting back those areas of consensus from diverse technical and community experts.

ASSESS

The success of the Assessment hinged on its ability to balance time constraints due to impending research funding allocations for DDT, while also allowing for meaningful engagement of relevant academic, government, industry, nonprofit, and community voices.

INVOLVE, RELATE, SITUATE

A multi-stage approach allowed for broad recruitment of participants through iterative "mapping" of interested parties and "snowball sampling" (*Involve*), where initial participants identified other potential participants, as well as provided participants with transparency into the evolving content of the Assessment report (*Relate & Situate*).

ENGAGE

Sea Grant consulted with NOAA's Office for Coastal Management and Coastal Training Program as well as an Advisory Committee of DDT experts to develop a multi-stage engagement process (i.e., interactive virtual workshop, asynchronous online activities, multiple listening sessions, one-on-ones) following best practices for facilitation, particularly in virtual formats.

ENACT & LEARN

The technical complexity of the DDT issue led to pivots in the engagement approach (*Engage, Enact, & Learn*), with listening sessions and one-on-ones replacing a participant survey to allow for more nuanced discussion, and the development of multiple outreach tools (i.e., handouts, short presentations) to set a common foundation of understanding before group discussions. The Assessment report ultimately informed a major California state DDT research funding call (Sea Grant California, 2023), and Sea Grant continues to facilitate a growing DDT community of practice.

BOX 3. ADDITIONAL ILLUSTRATIVE CASE STUDIES

Volunteer Beach Profile Monitoring Program

The New Hampshire Volunteer Beach Profile Monitoring Program (NHVBPMP), a collaboration among government, academic, and community partners, was created in 2016 in response to a need for more data-informed management options. It established long-term data sets of seasonal trends in New Hampshire (NH) beach elevation that continue to inform storm responses today. Given the complexity of coastal management decisions and the many people who study, work, recreate, and call coastal NH home, the co-production approach of citizen science was chosen for generating knowledge "by, for, and with members of the public" (*Assess*; Citizen Science Association, n.d.).

NH Sea Grant recruited local volunteers based on a shared interest of place (*Involve*). Community members were trained to collect monthly and post-storm beach elevation data using the Emery profiling method (Emery, 1961). A key intention of the project was for community volunteers to be project partners (*Involve*), not simply data collectors. This intention guided the development of project approaches (*Engage*). Significant time was allocated to develop and maintain relationships (*Relate*). Ongoing communication was maintained by phone, email, and field visits for scheduling, two-way feedback, and sharing stories and insights (*Enact*). Frequent communication helped to maintain data legitimacy through quality assurance and control measures (*Theme: Integrity*; Eberhardt et al., 2022).

Over time, trust has been built among partners, and power has shifted from the university to community partners (*Themes: Trust & Power*). Volunteers took on more ownership of the project, including sharing their perspectives on beach and dune dynamics through annual project meetings, field visits, phone calls, and email; modifying field equipment for greater accuracy; and reformatting data sheets (*Enact & Learn*). Following the approaches developed by Liboiron et al. (2018), a goal was to hear community partner interpretations of the data and perspectives on data validity and use (*Learn & Theme: Listening*). Rather than university partners sharing their synthesis of the data as might typically occur, this structure sought to intentionally shift power to community partners by prioritizing their input and consent to use the data (*Theme: Power*).

An annual survey of community partners provides an additional opportunity to prioritize input from community partners (*Learn & Theme: Listening*) and to gain insight on volunteer motivation—critical information for sustaining a program that meets the needs of its partners. Survey results also indicate increased motivation to take action on coastal issues as a result of participating in the project (Eberhardt et al., 2022), including sharing information with municipal boards.

This project is an example of how increased knowledge and motivation can result from the co-production approach (*Learn*).

Weaving Traditional Ecological Knowledge (TEK) and Science, Technology, Engineering, Arts, and Mathematics (STEAM) in a Climate Adaptation and Resilience Partnership

A partnership among the MIT Resilient Communities Lab, MIT Urban Risk Lab, Native Land Conservancy, GreenRoots, North American Indian Center of Boston, and MIT Sea Grant is addressing coastal adaptation and resilience in ways that are more equitable and better attenuated to traditional knowledge and the values of underrepresented communities in Massachusetts.

Although this partnership was launched in 2022, relationship-building was sparked by a 2019 workshop on "Coastal Resilience: Sharing Indigenous Knowledge and Experience" (*Relate*; Kumasaka et al., 2022), which included a presentation by Louisiana Sea Grant on a successful community decision process in coastal Louisiana (*Engage*; Bethel et al., 2011). After 2019, the Massachusetts group grew considerably as the number and geographic representation of participants increased (*Involve*) and ideas were exchanged and proposals co-produced for funding sources at regional and national scales through virtual, bimonthly meetings (*Enact*). When funding became available, a subset of this group formed a partnership, aiming to be responsive to local and state needs for planning in coastal adaptation and resilience (*Situate*).

At two sites, the partnership has been examining local restoration practices and principles that are cross-generational and organized around Indigenous cultural knowledge, language skills, the preservation of lifeways, and ecological balance in a rural and an urban setting (*Situate & Enact*). One site is a coastal pine barren ecosystem at Muddy Pond Wilderness Preserve, part of which is managed by and for Wampanoag tribes (*Situate & Enact*). Here, Indigenous land management practices and restoration projects offer a highly diverse educational portfolio for Indigenous and non-Indigenous youth (*Enact*). The other site is part of a coastal tidal estuary in Chelsea, which was heavily industrialized in the past and is one of the densest and most diverse cities in Massachusetts (*Situate*). Here, an environmental justice-focused community organization seeks the restoration of Mill Creek, aiming for resiliency and inclusion of Native knowledge by involving part of its immigrant population with Indigenous ancestry from Central and South America (*Involve & Engage*). The partnership has been convening community organizers, managers, planners, youth, and scientists (*Involve & Enact*), while continuing its learning and planning process for coastal resilience at these two sites (*Learn*).

For additional climate adaptation and resilience case studies, see Miller et al. (2024, in this issue).

Scientist and Fishermen Exchange (SAFE) Meetings

Sea Grant has a long history of Extension Specialists working directly with commercial fisheries in order to improve the health, efficiency, and sustainability of the fishing industry (Sea Grant, 2013). For example, Oregon Sea Grant has organized Scientist and Fishermen Exchange (SAFE) meetings for more than two decades (*Enact*), with the shared goal of building relationships and establishing trust and collaboration among commercial fishers, agency personnel, researchers, and other partners (*Relate & Engage, Theme: Trust*) (Conway, 2006). Regular meetings allow participants to listen and learn from diverse viewpoints while fostering mutual respect and understanding among participants (*Assess & Involve, Theme: Inclusivity*). SAFE provides a space to discuss emerging and ongoing concerns, ocean changes, and other topics of interest (*Engage & Enact; Theme: Listening*). A number of strong relationships, as well as ongoing projects based on co-developed research questions, have been initiated at SAFE meetings (*Situate, Engage*). Overall, these meetings allow these groups to build trusted relationships (*Relate, Theme: Trust*), identify areas for potential collaboration (*Assess*), and share information (*Enact;* NOAA, 2020).

the scientific communities. On the other hand, there may be conflicting needs, goals, or values. It is important to anticipate these dynamics and attend to them as they arise so that all participants have equitable access to the process and have their perspectives heard (see references in Vohland et al., 2021).

One effective way to identify key participants and ensure diverse representation is to collaborate with established community organizations, such as boundary organizations[1] and community-based groups. Because these organizations have established relationships and credibility within the community, they can facilitate direct engagement with key individuals, especially those who may be underrepresented or marginalized or respectfully represent the perspectives of community members who may not have the capacity to participate individually (Cash et al., 2003). Inclusion decisions should seek to balance local expertise with external support to better integrate diverse knowledge systems and to foster mutual learning and capacity building.

Situate Phase

The Situate Phase delves into understanding the context of engagement, including power dynamics, social structures, and governance systems (Figure 1; Boxes 1–3).

Each process of knowledge co-production is situated in a particular place, with a particular group of people, to address a particular problem or set of problems that are bound by a specific geography or framed by a broader issue (Nörstrom et al., 2020). In practice, how context is acknowledged and responded to determines whether the process of knowledge co-production is empowering for participants, whether the process and outcomes hold legitimacy, and whether the knowledge co-produced is relevant and impactful (Zurba et al., 2022).

Successful co-production is a process of "with" not "for," relying on developing shared understandings of engagement including participation, commitment, and objectives. It recognizes the self-determination of communities and Indigenous governance to approve or deny research (Zurba et al., 2022). It includes discussions of implicit and explicit perceptions, assumptions, and power (*Theme: Power*). Although it bucks a natural tendency to depoliticize co-production processes, power dynamics and inequities should be directly acknowledged and addressed (Turnhout et al., 2020, and references therein).

Engage Phase

The Engage Phase focuses on identifying specific goals and co-designing engagement, allowing participants to actively shape the knowledge generation process (Figure 1; Boxes 1–3).

Throughout this phase it is critical to co-design the goals of the co-production process through open, constructive dialogue among participants. Goals of the co-production process may be outcome or output oriented. Outcomes could include overcoming conflict, developing a shared understanding of an issue, defining a common vocabulary to address an issue, or ownership of research; outputs could include development of an actionable research tool or generating a publication of relevant/responsive/actionable research (Chambers et al., 2021). A portion of the established goals should be attainable within the planned project timeline while others may be longer term, achieved through continued partnership over time.

There will never be a "one-size-fits-all" approach to knowledge co-production, so it is important to collectively establish the co-production process (Schlüter et al., 2021, and references therein). Engagement level may vary based on goals and resources. Some processes may warrant full collaboration with a subset of participants, while targeted input can be solicited from others at specific stages. Additionally, co-production should strive for comprehensive representation, potentially expanding the group over time. However, to streamline the process, a core advisory group may need to be formed through mutual agreement (Beier et al., 2017, and references therein).

Effective co-production requires adaptability on the part of all participants as key details of the process evolve (*Theme: Flexibility*). Therefore, the project's scope and intended outcomes should allow the flexibility to meaningfully respond to participant input, including iteratively adapting project goals and processes as needed.

Enact Phase

During the Enact Phase, participants implement the co-production process. The end goals of this phase can vary and may take the form of research, specific actions, product development, or solutions to identified challenges (Figure 1; Boxes 1–3).

Implementation will be tailored to the key players, goals, and context. Often, activities within this phase can involve a combination of formal/informal and individual/small/large group interactions, but at least one meeting where all contributing parties are present is recommended (Beier et al., 2017, and references therein). In co-production processes it is important that "the resulting knowledge is perceived by participants and other end-users as credible, salient, and legitimate" (*Theme: Integrity*; Norström et al., 2020). Transparent communication on project scope, timelines, data, and goals establishes trust with communities, empowers community members, and democratizes project ownership. At its best, the process of knowledge co-production empowers decision-making and develops leadership in community members (Turnhout et al., 2020).

Identifying agreed-upon indicators to measure success, both before and during the enact phase, simplifies and enhances the transparency of the evaluation process, increasing

[1] Boundary organizations are intermediary organizations that produce information that is useful in policymaking and at the same time qualify as scientific (Wesselink and Hoppe, 2020).

the likelihood of achieving actionable change. Co-defining project benchmarks (e.g., reaching a certain milestone by a given date), values (e.g., inclusiveness, grounded in Indigenous epistemologies), and outcomes (e.g., educate a certain audience on a given topic) solidifies a shared understanding of the project's ultimate purpose and approach (Cooke et al., 2020).

Learn Phase

The Learn Phase emphasizes the importance of listening, evaluation, and reflection. This enables participants to learn from and during the co-production process and adjust strategies as needed, fostering continuous improvement and innovation (Figure 1; Boxes 1–3).

Listening throughout the entire process is important in order to evaluate the effectiveness of the co-designed process related to shared goals (*Theme: Listening*). This involves assessing implementation through unbiased, honest observation and reflection by all involved. Since impact and success can have various interpretations, assessments should be flexible and accommodate different perspectives on "success" among participants. Various principles of knowledge co-production may be used to assess the process: "context-based" aligns with the situation, "pluralistic" assesses diversity and mobilization of knowledge, "goal-oriented" targets outcomes, and "interactive" emphasizes the quality and evolution of interaction between participants (Norström et al., 2020).

As with the knowledge co-design process itself, the Learn Phase is iterative, with continuous refinement of implementation and evaluation strategies (Wyborn et al., 2019). Evaluation throughout the project allows for reflection on strategies that are serving or hindering project success, may reveal whether a pivot in the project goal or approach is necessary, and ultimately provides a way to share the story of the project's impact.

THE ROLE OF BOUNDARY ORGANIZATIONS IN KNOWLEDGE CO-PRODUCTION

The National Sea Grant Program as an Example

While many programs and funded projects support co-production of knowledge, Sea Grant's unique program model provides a structure that can overcome many of the challenges associated with participatory science frameworks and support the crosscutting guiding themes for knowledge co-production. The federal-academic partnership allows Sea Grant programs to tailor specific research priorities to address needs within their local communities, which are informed through extensive two-way feedback with partners. Case studies presented in Boxes 2 and 3 were selected to showcase how the theoretical assumptions of the wheel of knowledge co-production are grounded in practice and reflect examples across a diversity of participants, type of work, and maturity of projects. These case studies (Boxes 2–3), while not exhaustive, serve to highlight particularly noteworthy phases and themes in each process. Additionally, they illustrate the significant role of boundary organizations in knowledge co-production, exemplified by Sea Grant. Sea Grant's interdisciplinary approach and strong emphasis on centering communities in knowledge co-production provides a powerful platform for connecting researchers, communities, and practitioners to collaborate toward actionable solutions (Jones et al., 2021).

DISCUSSION

Boundary organizations can facilitate knowledge co-production by sharing membership across communities, translating across norms and vocabularies, and sustaining relationships and engagement over extended time periods. However, the journey toward effective knowledge co-production may present challenges (Jones et al., 2021) and may not always be the best approach for a given context. In many cases, clear incentives for engaging in co-production may not exist or may not align across participants; not all audiences value diverse forms of knowledge; there may be reluctance to engage in actionable science due to lack of training or interest; or the right venues for building initial relationships across people in different sectors or communities may not exist. Addressing these challenges is crucial, and this is where boundary organizations, like Sea Grant, along with other institutions and funding agencies, can make a significant impact. The unique role of boundary organizations and the functions and qualities of knowledge brokers should be recognized and further leveraged in advancing knowledge co-production efforts (Goodrich et al., 2020).

The wheel of knowledge co-production (Figure 1, Box 1) and the illustrative case studies (Boxes 2–3) highlight a few key recommendations for boundary organizations and those seeking to incorporate knowledge co-production approaches into their work. First, consider working with or through established knowledge brokers. These organizations' positions and standing relationships within communities can provide context to help researchers understand which communities are well served and which may be underserved and thus could benefit most from additional research. Assessment could extend beyond a project's funding period to capture the scope of measurable societal impact. Knowledge brokers can also help facilitate explicit conversations on incentives for co-production and navigate differences in needs across participants; provide relevant training in skills such as communication, engagement, and facilitation; apply social sciences and methodologies in an interdisciplinary context to help understand and address sustainability challenges; promote actionable knowledge; and develop environmental literacy to empower community members with the skills and knowledge needed for active participation in co-production efforts.

Funders can play a crucial role in incentivizing and rewarding knowledge co-production as well (Arnott et al., 2020a). Seed funding enables relationship and trust building, while longer-term grants reduce the pressure of continuous grant writing, allowing for more time spent engaging across phases of the knowledge co-production cycle. To make this process more intentional and authentic requires reimagining grant criteria, for example, in the development of requests for proposals (RFPs) that outline clear engagement objectives and evaluation criteria, shifting the focus from "box-checking" to genuine engagement and long-term relationship building. Additionally, providing longer lead times (e.g., many months at the minimum) for funding calls, funding all phases of the knowledge co-production cycle, and supporting participation costs (e.g., stipends, travel, meals, childcare) can allow partners to develop relationships (*Relate*), establish shared interest (*Assess*), identify key participants to include (*Involve*), understand the context of engagement (*Situate*), and co-design the goals and process (*Engage*) prior to carrying out the agreed upon project (*Enact*). These shifts in funding can further support genuine and sustainable knowledge co-production.

CONCLUSION

Our Iterative Work Ahead

This paper underscores the value of knowledge co-production as an interactive, participatory process that brings together diverse actors such as scientists, practitioners, and community members to collectively generate, integrate, and apply knowledge to address complex sustainability challenges. It serves as a guide for understanding when and how co-production can be effectively employed in community-based endeavors. As evidenced by examples from the National Sea Grant Program, co-production is a flexible, adaptive process, and projects do not all follow the same path. Some projects may even target specific phases of the process and therefore may become embedded within a larger, longer-term co-production process, spanning many projects.

We hope that the wheel of knowledge co-production (**Figure 1**) and associated resources (**Boxes 1–3** and additional readings) provided in this paper serve as a valuable starting point for researchers, practitioners, and communities engaged in or considering knowledge co-production approaches. Achieving knowledge co-production is a journey that involves learning, practice, and the gradual development of genuine and trustworthy relationships. Those who aim to promote this collaborative mode of work are in a constant state of learning and adaptation, which can extend into decision-making venues and participatory governance. Furthermore, we envision it as a cornerstone for shaping a collective vision of the central role that knowledge co-production plays in advancing actionable and equitable research. We hope that this work stimulates critical new thinking on how to address complex sustainability issues by centering communities in an equitable and inclusive process of shared knowledge generation and lays the foundation stones for a path toward realizing this vision.

SUPPLEMENTARY MATERIALS

Appendix S1: Author Contribution Criteria is available online at https://doi.org/10.5670/oceanog.2024.217.

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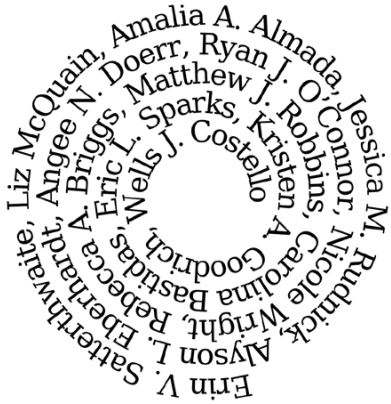

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