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Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice

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Abstract

Co-production has become a cornerstone of research within the sustainability sciences, motivating collaborations of diverse actors to conduct research in the service of societal and policy change. This review examines theoretical and empirical literature from sustainability science, public administration, and science and technology studies (STS) with the intention of advancing the theory and practice of co-production within sustainability science. We argue that co-production must go beyond stakeholder engagement by scientists to the more deliberate design of societal transitions. Co-production can contribute to such transitions by shifting the institutional arrangements that govern relationships between knowledge and power, science and society, and state and citizens. We highlight critical weaknesses in conceptualizations of co-production within sustainability sciences with respect to power,

politics, and governance. We offer suggestions for how this can be rectified through deeper engagement with public administration and STS to offer a broad vision for enhancing the use, design, and practice of a more reflexive co-production in sustainability science.

Contents

INTRODUCTION

Sustainability challenges are complex, contested, and plagued by uncertainties, and they often face social, cultural, and political barriers to change. Addressing them requires diverse expertise in combination with appropriate societal choices, policies, and practices. This entails reordering social, economic, political, and technological practices and arrangements, on scales from the local to the planetary, around new insights into their dynamic relationships with ecological systems. Sustainability science has built an ambitious research agenda to illuminate those challenges, their complexities and uncertainties, potential solutions, as well as diverse barriers to action (1). To date, however, the field's research has fallen short of empowering the sort of far-reaching, systems-level transformation necessary to achieve global sustainability (2).

For the past two decades, sustainability science has focused on transforming how science is conducted to create new knowledge to progress the sustainability agenda. It is not enough, however, to do science differently. Realizing sustainability goals also requires changing how decisions are made, and how they draw on scientific and other knowledge. To do this, science needs to be positioned differently in the world, through integrating new ways of knowing into new ways of making decisions and acting across all spheres of social, economic, and political life. Such integration can be enhanced through processes of co-production, which we define as the following: processes that iteratively unite ways of knowing and acting—including ideas, norms, practices, and discourses—leading to mutual reinforcement and reciprocal transformation of societal outcomes.

Sustainability: meeting the needs of present and future generations through approaches that address current inequalities while conserving Earth's life support systems

Understood this way, co-production encompasses many ambitions, namely to involve multiple participants (scientists, policymakers, civil society, etc.) to produce multiple outcomes, including new knowledge, new ways of integrating knowledge into decision making and action, and, most importantly, new outcomes in the world (3). However, to date, sustainability science has largely defined co-production in terms of new ways of producing science. We suggest that this

Table 1 Definitions of co-production

Author	Definition
Sustainability sciences	
Kates et al. (4)	"[S]ustainability science must be created through the processes of co-production in which scholars and stakeholders interact to define important questions, relevant evidence, and convincing forms of argument." (p. 2)
Cash (5)	"…[T]he concept of co-production—the act of producing information or technology through the collaboration of scientists and engineers and nonscientists, who incorporate values and criteria from both communities." (p. 467)
Lemos & Morehouse (6)	"Co-production of science and policy…requires substantial commitment to…interdisciplinarity, stakeholder participation, and the production of knowledge that is demonstrably usable." (p. 66)
Cornell et al. (7)	"When viewed as a learning process, sustainability research can be conceptualised as the co-production of knowledge arising from the engagement of multiple knowledge producers." (p. 63)
Public administration	
Ostrom (8)	"[T]he process through which inputs used to produce a good or a service are contributed by individuals who are not 'in' the same organisation…. Co-production implies that citizens can play an active role in producing public goods and services of consequence to them." (p. 1073)
Brudney & England (9)	"[T]he coproduction model is defined by the degree of overlap between two sets of participants—regular producers (e.g., service agents, public administrators) and consumers (e.g., citizens, neighborhood associations). The resultant overlap represents joint production of services by these two groups, or 'co-production.'" (p. 63)
Bovaird (10)	"[T]he provision of services through regular, long-term relationships between professionalised service providers (in any sector) and service users or members of the community, where all parties make substantial resource contributions." (p. 847)
Alford (11)	"Co-production is any behavior by anyone outside a government agency which: ■ is conjoint with agency participation, or is independent of it but prompted by some action of the agency; ■ is at least partly voluntary; and ■ either intentionally or unintentionally creates private and/or public value, in the form of
Science and technology studies	
Jasanoff (12)	"Increasingly the realities of human experience emerge as the joint achievements of scientific, technical and social enterprise: science and society are, in a word, *co-produced*, each underwriting the other's existence." (p. 17)
Shapin & Schaffer (13)	"Solutions to the problem of knowledge are solutions to the problem of social order." (p. 332)
Jasanoff & Wynne (14)	"Scientific knowledge and political order are co-produced at multiple stages in their joint evolution, from the stabilization of factual findings in laboratories and field studies, to the national and international acceptance of causal explanations offered by science and their use in decision-making." (pp. 6–7)
Forsyth (15)	"The term refers to the processes by which knowledge, including scientific knowledge, is framed, collated, and disseminated through social interaction and change, and how such knowledge also impacts upon such change…. [T]he important principle of co-production is that it is a *dynamic* process, in which knowledge and society continually shape each other." (p. 104)

conceptualization is limiting. Our more expansive notion of co-production draws on definitions from sustainability science, public administration, and science and technology studies (STS) (see **Table 1**), to point to the broader context in which co-produced knowledge is used and with a clear normative objective to support societal change.

Co-production: processes that iteratively bring together diverse groups and their ways of knowing and acting to create new knowledge and practices to transform societal outcomes

Our review is comprised of two parts. In the first part, we provide an overview of foundational theoretical texts from the core intellectual heritage of co-production across sustainability science, public administration, and STS. In the second part, we review empirical experiments in co-production drawn from sustainability science and public administration. These fields share a focus on the use of co-production to bring together people with diverse backgrounds to produce public goods and services. Synthesizing the collective insights from theory and practice, we offer suggestions for how sustainability science can more fully embrace both the theory and practice of co-production in the service of helping humanity achieve sustainability. We conclude by highlighting fertile areas for future engagement between research and practice in the field of co-production. However, first, to ground this review, we offer a brief overview of the history of co-production and some of its recent critiques.

CO-PRODUCTION AND ITS CRITIQUES

The present-day significance of co-production as a research practice in sustainability science and other areas of policy-focused research (see, e.g., 16) builds on a long history of developments in science and research policy (see **Table 2** for a detailed description of antecedents to co-production). Calls "to do science differently" (see, e.g., 17–19) have ranged from transdisciplinary research, action research, mode-2 science, postnormal science, and more recently, knowledge co-production. These approaches emphasized the public benefit of science, the need for interdisciplinary knowledge to meet today's societal challenges, and the need for scientists to work with those beyond

Table 2 Antecedents to co-production

Concept	Description
Participatory action research	In participatory action research, researchers and stakeholders design and undertake cooperative, iterative cycles of action, reflection, and research. They define a desired goal or vision for the future and undertake actions that will expand knowledge, enhance competencies, and overcome challenges to realizing a goal (21). Action research embeds implementation activities into the research process, and encourages reflection on them.
Mode-2 knowledge production	Mode-2 was developed to describe the changing relationship between the governance and production of research (18). In Mode-2, knowledge production is socially distributed, action-oriented, transdisciplinary, and subject to multiple accountabilities. It suggests that, rather than there being a one-way flow of information, science "speaks" to society and society "speaks back" to science.
Transdisciplinary research	Transdisciplinary (TD) research is conceptualized in many ways. Most definitions include references to multiple scientific disciplines coming together with nonscientific perspectives. Others suggest that TD must address societally relevant problems, enable learning across disciplines and with societal actors, and create knowledge that is credible scientifically, socially robust, and usable among relevant groups (22).
Postnormal science	Postnormal science is concerned with addressing complex problems in contexts where there are high stakes and uncertainties, values are in dispute, and decisions are urgent (23). Here scientific knowledge cannot provide simple and uncontested answers about what to do. Debates over values and desirable futures are central; thus, plurality of legitimate perspectives must be brought into dialogue, leading to mutual respect and learning to support decision making.
Civic science	Civic science is an umbrella concept that draws together different forms of public participation within the production of science (24). This includes terminology such as participatory, civil, civic, stakeholder, and democratic science—all of which point to the changing relationship between the public and experts. Civic science can have differing goals: diversification of representation in science, increased citizen participation, and democratization of science. These all focus on what the public and citizens have at stake in activities at the science-policy interface, and their outcomes.

its institutional borders. Although this conceptual evolution sparked questions of whether co-production is "old wine in a new bottle" (20), the challenge remains how to reconfigure science and its relationship to decision making and action to achieve societal goals.

There are great expectations embedded within current conceptualizations of co-production. This review critically examines and subsequently contributes to the promise of achieving new knowledge and outcomes in the world through co-production processes. However, to understand the promises of co-production, one must also recognize its limitations and criticisms. Indeed, the growing emphasis on co-production in sustainability science is not without critique. Some have questioned whether co-production can meet the promises of ameliorating complex problems (25–27), and point to the lack of evidence supporting claims of outcomes and impact (20, 26, 28). Recent critiques have cautioned that the costs of co-production may outweigh the perceived benefits. Costs range from often cited issues of time, resources, and conflict to more profound challenges to the perceived usability and credibility of evidence and reputational damage to researchers (28). Others have questioned a perceived overly local orientation of co-production, arguing that co-production is only worth the investment when it contributes to a global knowledge base, calling instead for localized processes of coassessment (29). This perspective mischaracterizes co-production as primarily involving the localization of knowledge, ignoring the rich history of theory (see, e.g., 30) and emerging practice focused on co-production at global scales (see, e.g., 31). As a result, this critique reinforces a paradigm that elevates "global" expert knowledge and economic efficiency above local knowledge and other socioecological outcomes, based on judgments about the cost and value of knowledge production, who bears these costs, and whether the resulting outcome is commensurate with existing reward structures within traditional models of science (32).

Other critics argue that co-production within sustainability science (33) and health research (28) often fails to adequately account for power within science-society relationships. Such a perspective invites questions regarding whose knowledge is being co-produced—for which outcomes, to the benefit of whom, and who decides (20, 33–37). These concerns have been raised with respect to the recent proliferation of principles and how-to guides for co-production (see, e.g., 20, 36). These critiques highlight potential incommensurability between research that is accountable to decision makers and that which seeks to challenge the status quo. Accordingly, producing knowledge that has direct utility to those currently in power can institutionalize particular problem framings, reinforcing the power of policy elites or those who have the time and capacity to engage, and thereby marginalizing those with less capacity or alternative perspectives (33, 34, 36, 37, 38). This can be problematic when the processes used to evaluate and select stakeholders, viewpoints, and knowledges for inclusion are not transparent, or do not engage with the ontological and epistemological tensions inherent across different ways of knowing.

Critics of co-production challenge calls to "engage with all stakeholders" and "understand users' needs" without clear consideration of power and politics. The significant investment of time and resources required to support co-production can create ethical issues around the participation of self-identified and often unpaid stakeholders who, by nature of their participation, have a strong voice in representing a particular problem framing (28). Concerns have also been raised about presenting co-production as a panacea, pointing to value conflicts and the dilution of public accountability that occurs when processes blur boundaries between sectors (10).

These critiques offer key correctives to—but do not undermine the need for—the practice of co-production, which is now institutionalized in major global research and policy processes (e.g., Future Earth) and required by many funding agencies (e.g., the Belmont Forum). Researchers around the world are experimenting with methods and tools for co-production. Given this activity, more deliberate engagement between critical scholarship and the practice of co-production can

provide pragmatic guidance on ways to situate co-production practices within their sociocultural, political, and normative contexts. This in turn can help co-production transform both science and governance to achieve local and global sustainability (39).

Governance: processes and structures shaping individual or collective action solidified through institutions

Institutions: formal rules, informal norms, or shared understandings that structure political, economic, and social interactions

Responding to these critiques should begin with a robust discussion about when, in what contexts, and using what practices co-production processes are appropriate and effective, and how they can be designed in an appropriately inclusive fashion (28). Pluralist perspectives call for processes that encourage reflexivity through inclusion of diverse actors, interests, and understandings in ways that open up, rather than close down, problem definitions (34, 35, 38). Pragmatic, efficiency-oriented perspectives call for optimal allocation of resources through working with those who can directly contribute to addressing the problem at hand (29). These perspectives can be reconciled by an approach that, first, has a broader appreciation of the governance context in which co-production processes take place and how this enables or constrains effective collaboration between diverse stakeholders. Such an assessment can be used to determine whether co-production is indeed the appropriate choice for a given context (28). Second, if co-production is the chosen modality, practices need to acknowledge the realities of politics and dissent while navigating tensions and trade-offs among different ways of knowing and notions of desirable pathways toward sustainability.

The canvasing of these recent critiques of co-production offers insights from which to reflect upon recent lessons in the theory and practice of co-production. We now address these through a review that builds on and expands recent reviews of co-production (see 4, 25–28) by engaging with a broader multidisciplinary body of the theory of co-production.

CO-PRODUCTION IN THEORY

This section provides a theoretical synthesis to illustrate how co-production has been interpreted and debated within sustainability science, public administration, and STS. As suggested above, the broader objectives of sustainability science require the simultaneous transformation of both science and governance. By bringing public administration and STS effectively into conversation with sustainability science, we see the opportunity to expand conceptualizations of co-production beyond the production of knowledge to realize the goals of changing institutions and producing societal outcomes.

Co-Producing Science for Sustainability

For sustainability science, co-production provides a framework to rethink science and its connection to society as a tool to meet grand societal challenges. Sustainability science reoriented science (and scientists) from purely a provider of information to a partner in negotiating and ultimately co-producing shared knowledge, either with other groups of knowledge holders, such as indigenous communities (see, e.g., 40), or with decision makers (see, e.g., 6). To accomplish this, co-production provides a means to an end: improving the usability of scientific information by those beyond academia who are looking to science for answers to sustainability crises. Usability emerges in theories of sustainability science through more direct engagement with societal actors (41, 42). Sustainability scientists contend that co-production processes generate a better fit between scientific research, other ways of knowing, and the issues and contexts faced by decision makers, and therefore are better placed to generate innovative and actionable solutions (43). Cash et al. (41) argued, for example, that efforts to improve the credibility, salience, and legitimacy of science would all improve its ability to serve as "usable" knowledge. Building on this framework, approaches to co-production in sustainability science have sought to supplement scientific

credibility with additional criteria of relevance and salience to practitioners (generated through negotiated framing and agenda setting for research) and ensuring its social and political legitimacy (by incorporating norms of participation, inclusion, and consultation into the design and conduct of research).

Knowledge systems: the knowledge claims, values and standards, epistemologies, and structures that shape knowledge use

Creating usable or actionable knowledge thus requires careful attention to the design, structure, organization, and dynamics of co-production processes. Situating co-production processes within a broader context places attention on knowledge systems, defined as sets of social and institutional arrangements for producing, communicating, and applying knowledge (44–46). Within knowledge systems, co-production processes occur across multiple stages, e.g., through codesign, co-production, and codissemination (22, 42). Similarly, the concept of a "knowledge arena" brings diverse perspectives together to develop a common vision, integrate knowledge, implement actions, and learn from experience (7). Emphasis is often placed on codesign, the first phase of knowledge co-production. This is said to be a critical time for framing and generating knowledge, building capacity among participants, and developing pathways and coalitions to mobilize transformative change (see, e.g., 47).

Building on this idea, recent work on co-production focuses on iterative and inclusive processes that are responsive and adaptive as conditions change and as participants acquire better understandings of both the problems they confront and each other's ways of knowing (48–51). For example, studies of regional climate assessments find iterative engagement between science and policy makers critical to improving the usability of science (6). This iterative dialogue has to be "owned" by individuals or organizations tasked with building the conditions and mechanisms for climate assessments and their use (52). Such iterative and long-term engagement processes can develop common ground, mutual understanding, and trust necessary to address controversial challenges (53), and can build enabling capacities to integrate science with enhanced engagement of diverse stakeholders (40). Such learning is said to help develop co-productive capacities: new capabilities to collectively mobilize in support of scientifically informed social change (39).

Sustainability science as a field has been criticized for undertheorizing the complex social, organizational, and political domains within which science gets co-produced alongside sustainability policy (54). However, as we have discussed above, the field has been largely focused on using co-production ideas to alter the practice of science and, therefore, on engaging science communities in alternative approaches to knowledge production. Sustainability science scholars have made substantial contributions to reshaping the production of science as an input to sustainability policy, planning, management, action, and change. There has, however, been considerably less focus on the co-production of sustainability policy or governance. That project has been the province of research in public administration.

The Co-Production of Governance

The field of public administration is principally concerned with the development and implementation of policy and programs by governments. Within this focus, theorizing about co-production has emphasized processes whereby the state and citizens collectively produce public goods and services. This literature covers a wide range of topics, including health care services, community development, aged care, policing, urban services, disaster risk management, and beyond. Early scholarship focused on the inability of governments to deliver public services such as public safety or education without an active citizenry (55, 56) and on strategies for addressing this challenge through the active partnership of citizens in governance processes. This approach to co-production resonated strongly, especially in the 1980s, with shifting conceptions of the public sector: antipathy toward big government, growing interest in citizen participation, expanding

notions of citizenship (10, 11), and increased emphasis on the contribution of the third sector to public services provision (57).

One of the foremost thinkers in this field, Elinor Ostrom, defined co-production as "a process through which inputs used to produce a good or a service are contributed by individuals who are not 'in' the same organization…. Co-production implies that citizens can play an active role in producing public goods and services of consequence to them" (9, p. 1073). She argued that education, for example, cannot be produced by teachers alone: It requires the active collaboration of students, education policy makers, parents, and others (55; see 3 for a longer treatment of Ostrom's early work). Parks et al. (56) frame co-production as the "mixing of productive efforts" through either coordinated efforts or through independent yet reinforcing efforts of regular producers of public services (i.e., government agencies) and their consumers (i.e., citizens). Brudney & England (9) further define co-production by the "degree of overlap" in the production of public services between government agents, public administrators, and citizens and neighborhood organizations. Critically, this scholarship demonstrated that the production of public goods and services emerges through the interactions of multiple public and private actors, each with agency to influence how those services are produced (8). These co-production processes are transformative: Citizens transform service delivery and are themselves transformed in the process (8, 57). This transformative perspective is inherently political, as co-production practices within public administration explicitly seek to reconfigure relationships between the state and citizen.

Within public administration, interpretations of co-production vary across five key questions: First, who represents "the citizen" in the relationship between state and citizen—the individual or community organizations? Second, what is being co-produced—outputs or outcomes? Here outputs are understood to be intermediary products that potentially lead to community outcomes; e.g., a plan for community safety is the output, whereas community safety itself is the outcome. Third, what kinds of activities should be counted within the process of co-production—intentional or unintentional activities, transactional or relational interactions, activities undertaken voluntarily or through compliance? Fourth, what forms of activities are considered within co-production, e.g., planning, design, management, or service delivery? Finally, what types of institutional arrangements, processes, and capacities support effective collaboration between the state and citizens (9–11, 57)? It is this final area of research that has the greatest potential to contribute to furthering co-production within sustainability science.

The public administration literature provides substantial insights into the processes, means, and capacities required to bring diverse perspectives into practical action through the design of rules, incentives, and other institutions (58). Early scholarship considered how broader institutional arrangements between the market, state, and civil society shape the nature and function of co-production (see 8, 56) as well as the potential for co-production processes to challenge or redistribute power dynamics within existing relationships between the state and citizens (8, 9). By drawing attention to the higher-scale institutional contexts, public administration scholars have demonstrated that effective co-production requires more than the good will and effort of those engaged in the process. Rather, aligned structures and institutions enable (whereas misaligned ones undermine) collaborative decision making. This includes empowering, not just informing and consulting, citizens; synergies and co-dependencies between contributing parties; commitments among participants to one another and to the process; incentives for both public officials and citizens to participate; governance mechanisms that can monitor compliance and shirking of responsibilities; and flexible governance that allows for experimentation and failure (8, 10, 56).

Although the requirements of co-production likely create inefficiencies in governance processes, Parks et al. (56) correctly foreshadowed that co-production would grow in popularity within

the context of budget constraints and increased awareness of the importance of consumer inputs to public service delivery. This popularity has led to several policy experiments and institutional arrangements that are informative for co-production within sustainability science and action and which we review in the section Co-Production in Practice. Although she did not use the term co-production, Ostrom's later research on the governance of the commons mirrors the basic concept advanced in her and her colleagues' early work on co-production: The state cannot manage the commons without the active collaboration of the people who inhabit and use it (3). The public administration literature, however, largely overlooks the role of knowledge or science as a key element in the co-production of governance (although 59 is a notable recent exception).

Co-Producing Science and Governance

The ways in which science and governance are co-produced is the province of research in STS. Broadly construed, STS research focuses on how knowledge is produced, validated, and used as an integral part of social dynamics, emerging from and, in turn, shaping social processes and arrangements. Unlike sustainability science and public administration, where co-production tends to be conceived as an intentional practice, within STS, co-production is a theoretical lens through which to analyze the complex, existing relations of science and governance; in other words, co-production is "an idiom—a way of interpreting and accounting for complex phenomena" (13, p. 3). Analyses are often developed around in-depth empirical research, such as interviews, ethnographies, or detailed historical analysis of, for example, the emergence of the concept of old-growth forests (60), the development of policies to regulate air quality (61), or the organization of global climate governance (30).

The resulting scholarship highlights that science is a product of the design of particular sociopolitical and institutional settings that shape the kinds of knowledge that get produced, validated, and used (62). At the same time, STS research emphasizes that science plays a critical role in defining, stabilizing, and constituting social order (63). The idiom of co-production developed as a means to make sense of how knowledge is both product and producer of the natural and social systems in which it emerges. Over time, two primary approaches have emerged to examining co-production within STS: the constitutive and the interactional (12).

Constitutive STS examines how social and natural orders are created together. This work sees the world not as predelineated into the categories of nature and culture, but rather as hybrid networks that are constructed and assigned categories by humans and their institutions (64). Here, the emphasis of co-production is on the relational ontology between nature and society; the making of one shapes the making of the other. Such scholarship often examines how hybrid networks of humans and nonhumans are constructed and made durable through their complex relations (65). According to this perspective, power is accumulated through the creation of strong social networks in which humans interact with other physical objects, such as buildings or books, to achieve their goals.

Interactional STS focuses, by contrast, on the ways in which human agency and conflicting values play out in relations between science and the state. The place of knowledge and power in the making and maintaining of cultural and historical norms is central to this inquiry (12). It examines the ways in which values both embed, and are embedded in, the institutions, discourses, identities, and representations through which we know and act in the world (12). Knowledge of global climate change, for example, was made possible by the emergence of international networks of scientists and technological advances that could facilitate the sharing and comparing of data (30). In parallel, the new global perspectives that this knowledge provided provoked a rethinking of how political communities should organize themselves to combat climate change (66).

Knowledge governance: the formal and informal institutions that shape the creation, sharing, and use of knowledge

In making these analyses, the co-production idiom is used to show that knowledge and social order align in stable relationships and work together to maintain that stability over time. For thinking about sustainability, this means that making significant changes in societal configurations to achieve social and environmental goals not only requires altering the ways in which knowledge is produced, but also the ways in which knowledge is acted upon, reflecting the ways governance and society are organized to pursue sustainability. The co-production idiom in STS brings different articulations or framings into sharp relief: problems and solutions, facts and values, or means and ends. These ways of representing knowledge are not given in nature but are co-produced outcomes. Although the descriptive accounts of co-production within STS often stop short of presenting solutions or policy options, these accounts can provide critical insights when incorporated into attempts to practice co-production.

Despite different conceptualizations of co-production within sustainability science and STS, there has been considerable cross-fertilization and interactions across these bodies of literature. Notable contributions therein concern knowledge governance and knowledge systems analysis, which are driven by a desire to move beyond the focus on a particular intervention to understand how knowledge practices are situated within and shaped by social contexts, social and cultural norms, and their manifestation in institutional arrangements (45, 46). Sharing a focus on institutions of co-production with the public administration literature, the knowledge governance approach focuses on the formal and informal rules that shape the creation, sharing, and use of knowledge, whereas knowledge systems analysis focuses on the knowledge claims, values and standards, epistemologies, and structures that shape knowledge use (44). Critically, both approaches offer insights into the societal foundations—be they cultural, institutional, or epistemological—that enable or constrain efforts to produce and utilize new knowledge to advance sustainability.

Other productive cross fertilization has occurred within scholarship on adaptive governance (3), highlighting the capacity to navigate uncertainty, complexity, and rapid environmental change through mechanisms that support social learning, knowledge partnerships, and adaptive management. Adaptive governance researchers have, for instance, analyzed normative commitments of environmental governance (67) and the processes that facilitate dialogue among local, traditional, and scientific knowledge at local (40) and global scales (68). Such studies highlight how power has an effect on engagements between science and other forms of knowledge in decision-making processes.

Theorization of co-production within STS provides four key avenues to interrogate and inform sustainability science and action. First, recognizing that material objects have a role to play in creating networks and wielding power means that graphs, farms, animals, and computer models can all be seen as agents within co-production processes, with the potential to shape and be shaped by the resulting outcomes. Second, highlighting differences in cultural and historical norms that are frequently invisible to those that enact them shows how culture can shape the way science is perceived and structure its role in decision making. Third, by unpacking the role of institutions (rules and norms) in governing the relationships between knowledge production and decision making, and between citizens, scientists, and decision makers, the STS idiom can aid our understanding of how institutions change over time and are different from place to place. Finally, and relatedly, analyzing how institutions are partly driven by shared ways of speaking and thinking about challenges—through discourses—can foster critical reflection on the stories that are used to constitute reality. For example, conservation discourses of the relationships between humans and nature, and their relative importance to conservation research, have changed over time (69). The concept of co-production suggests that such discourses contain embedded assumptions about how science is (and should be) done, as well as its potential roles in policy and broader democracy (70).

A HOLISTIC CONCEPTION OF CO-PRODUCTION THROUGH DESIGN

The principle difference between these three distinct theories of co-production is often taken to be normative. Sustainability science and public administration seek to use co-production as a form of intervention, changing the practice of science and governance to generate new knowledge for sustainability that can be used more effectively to advance sustainable governance (42). STS seeks to use co-production to examine how science and governance are already enacted together, and to critically unpack the power dynamics enmeshed in such relationships (46). This difference can be overstated, however (3). Key contributors to STS theories of co-production, including both Latour and Jasanoff, for example, have devoted their careers not only to analyzing the co-production of science and governance but also to intervening as experts and practitioners in that co-production toward diverse normative ends, including enhancing sustainability, inclusivity, and democracy.

More importantly, these fields share a common foundation in emphasizing the significance of the design of scientific and policy institutions and processes and their relations. STS analyses have merely deepened and reinforced the insights of sustainability science and public administration: All science is a product of sociopolitical and institutional settings; all governance involves citizens in some way; and all societal outcomes, including sustainability outcomes, are shaped by the design of processes for creating knowledge and incorporating it into the fashioning of society. Advancing sustainability is, therefore, as all three fields have long suggested, a matter of redesigning science and governance and their relations along different, more sustainable alignments. STS insights do not alter that fundamental conclusion, they merely insist the task is more complex and political than can be captured through simple design models. Doing co-production well is therefore an exercise in carefully considering the design of co-production processes and capacities and their fit with broader institutions.

These collective insights provide the foundation for a nested conceptual framework of designing and doing co-production in sustainability science and action (see **Figure 1**). Sustainability science points attention to the value of bringing diverse expertise into co-production interventions and the practices that support improved dialogue across multiple forms of expertise in order to expand the knowledge base for sustainable development outcomes. This tacitly acknowledges that inclusivity is a concern not just for political processes but also for the epistemic processes that underpin them, as STS has emphasized. Public administration expands our understanding of the breadth of outcomes that can result from co-production processes and the institutional context in which they are situated and highlights that the design of co-production should incorporate both knowledge processes and outcomes as well as governance processes and outcomes. Public administration attends specifically to the ways that existing systems of policies and institutions enable or constrain effective co-production interventions and, therefore, highlights the value of increased capacities to alter existing scientific, policy, and institutional arrangements as an outcome of co-production that can lead to improvements in sustainability outcomes. The field of STS, in turn, gives us the tools to critically analyze how the designs of science and governance work together to advance or degrade sustainability, inclusivity, and justice in human affairs. STS deepens our understanding of how existing social and cultural norms interact with co-production, which can inform attempts to design co-production processes that interact constructively, rather than destructively, with the broader societal context in which they are undertaken. The reciprocal nature of relationships between knowledge and society, and even between interventions and society, makes it necessary to consider how interventions are situated within, and coconstituted by, social and cultural norms as well as existing systems of policy and institutions. These relationships

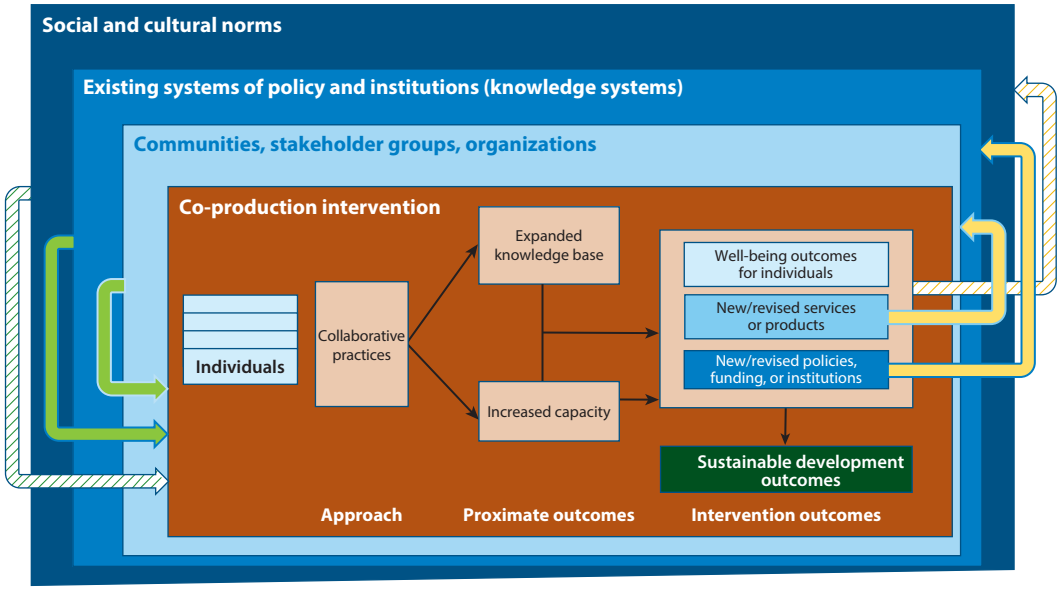

Figure 1

Nested conceptual framework of co-production. The blue boxes represent nested layers that shape and are shaped by each other to create the sociocultural conditions under which a given co-production intervention is situated. Green arrows represent the influence of the context on a co-production intervention; the solid green arrows are elements that can potentially be controlled or shaped, and the striped green arrow represents elements that cannot be intentionally influenced but nonetheless impact the process and therefore should be acknowledged. Yellow arrows represent the outcomes of a co-production intervention and the ways they can feed back to influence existing elements of the context of the intervention. The striped yellow arrow represents the diffuse and reciprocal impacts on the social and cultural norms of a context as described by the science and technology studies idiom. Figure adapted from Reference 46.

should be considered when designing the process and when determining desired outcomes of co-production processes.

The conceptual framework highlights the different arenas in which co-production interventions can have influence. Specifically, co-production processes differentially impact individuals; communities, stakeholder groups, and organizations; and existing systems of policy and institutions—and the design of co-production processes determines what forms these impacts take. The design of co-production is not simply about what scientists and their partners do in making science more usable and putting it to work in sustainability policy but also how that work relates to and interacts with existing systems, structures, and processes of policy and institutions. Although outcomes in these arenas are the predominant focus of sustainability science and public administration, the STS literature illustrates that such changes, either intentionally or unintentionally, are both embedded in and reciprocally shape broader social and cultural norms of the intervention. This framework is intended to illuminate the nested, interacting scales that simultaneously shape co-production interventions. Being aware of these interactions makes it possible to consider the broader context in the design process, and to be more aware of the intentional or unintentional impacts of an intervention beyond its immediate focus. There is no failsafe way to ensure an intervention reaches its desired outcomes and avoids unintended consequences, but to be aware rather than blind to these reciprocal interactions with context may allow actors in an intervention to better prepare for them. Improvement is an inherently subjective determination that

is likely to be considered relative to how people are positioned in relation to the co-production process and its intended outcomes. We use this framework to structure the empirical review that follows and conclude with suggestions for how to inform future theory and practice of co-production.

CO-PRODUCTION IN PRACTICE

We now turn our attention to how concepts of co-production have been used in practice and what outcomes these efforts have achieved. This section draws on a systematic review of 100 empirical studies involving co-production processes published in the past five years, representing a broad sweep of literature across public administration and sustainability science (see the **Supplementary Materials** for detailed methods). Case studies from public administration generally focus on public service delivery, including health services, where co-production is widely practiced and reported on, as well as other sectors where co-production appears less extensively institutionalized but still frequently experimented with. Within sustainability science, we consider case studies of projects focused on issues ranging from urban sustainability (71, 72) to climate adaptation (73) to ecosystem services (74, 75). While the specific problems addressed by public administration and sustainability science differ [e.g., community sanitation issues (76) versus developing local-level climate change responses (77), respectively], actors in both fields seek to engage diverse participants from different sectors or disciplines, to create or improve available knowledge of a given issue (78, 79), services [e.g., clean drinking water (80)], products [e.g., maps (81)], or other public goods. Insights from a synthesis of the motivations, outcomes, and recommendations from both fields provide relevant recommendations for researchers and practitioners aspiring to enact co-production in the realm of sustainability.

Situating Co-Production: Definitions Across the Literature

Definitions of co-production across the public administration and sustainability science fields generally include at least two elements: First, co-production involves diverse actors that do not work together in traditional models (e.g., doctors and patients, researchers and local communities), and second, this joint effort results in some product, service, or body of knowledge that contributes to addressing an issue of shared concern. Within this literature, Ostrom's definition is widely referenced in both public administration (82–85) and sustainability science (86, 87). The STS idiom features less prominently in sustainability science (80, 88–97) and rarely in public administration (98). The few studies that do reference co-production as an idiom tend to draw on Jasanoff's focus on the coevolution of knowledge and social order (12). The idiom is commonly invoked within discussions about catalyzing social change (90), to understand how or why new knowledge is or is not accepted and institutionalized in policy and practice (88, 94–97), and to encourage use of the lens by those practicing co-production in order to more explicitly consider existing power dynamics in the relationship between science and society (91–93).

Many studies in public administration and sustainability science do not explicitly define co-production. Very few studies acknowledge the multiple frames for co-production, with a few exceptions within sustainability science (88, 99–101) and the health sciences (102, 103). Failure to define, or to recognize the different uses of, co-production and the diverse ways it is practiced not only makes the aims of a given study unclear, but also risks furthering confusion around the concept as its use grows in research and practice. Future studies must clearly define their use of the term, how it is operationalized, and to what ends if such confusion is to be avoided.

Outcomes of Co-Production

Motivations for co-production arise from a wide range of desired outcomes (see **Table 3**), including but not limited to the logics of accountability, impact, and humility (100) and the descriptive and normative lenses (104) previously articulated in the literature. Desired outcomes range from improved process, e.g., increase equity in decision making and research (105, 106); to new outputs, e.g., improve the knowledge base for delivering public services (81, 84, 105–111); and finally to long-term outcomes, e.g., address the failure to produce services or knowledge that equitably meet the needs of users (112, 113) (see **Table 2**). Many projects lean toward the latter; public administration studies primarily focus on the delivery of services or products, whereas sustainability science tends to focus on the production of new knowledge or on improving the usability of science.

Reported actual outcomes of co-production processes vary widely across the literature and are summarized in the far-right column of **Table 3**. Co-production processes were found to redistribute power (76, 114, 115), allow for creativity (116), and encourage reflexivity among actors (117). Intermediate outputs generated through co-production generally relate to the creation of new knowledge, deepened understanding, or broader awareness of a given issue (e.g., 71, 99, 101, 118–123); it is evident from these studies that researchers, practitioners, citizens, and politicians can gain or generate new knowledge through co-productive processes. Other intermediate outputs primarily involved increasing capacity by involving nontraditional actors bolster available skills, knowledge, and time (99, 111, 120, 124, 125).

The ultimate outcomes of co-production interventions impact the individual, community, and even knowledge systems scale. These outcomes relate back to the different layers of influence an intervention can have on the context in which it is situated, as the arrows on the right side of **Figure 1** represent. There were also a few studies that engaged constructively with the context of co-production interventions by employing the STS idiom of co-production (see, e.g., 89, 91, 95). This idiom enables actors to consider the influence of the often unquestioned social, historical, and cultural norms of knowledge processes that underlie societal processes, and explicitly recognizes that knowledge processes inherently shape these norms (39, 126, 127). Studies that employed this idiom were motivated by a desire to reframe environmental problems, and to demonstrate how actors can use co-production to change societal power relations, particularly related to the way different types of knowledge are or are not privileged in decision making. A few studies illustrate how the STS lens provides insight into the factors that prevent acceptance of potentially useful knowledge in policy and practice, which may in turn allow participants to recognize and subsequently challenge power structures that generate inequities between stakeholders (see, e.g., 90, 92).

Recommendations for the Design of Co-Production Processes

Here we synthesize a broad range of recommendations from recent literature that can usefully inform co-production processes. We focus predominantly on recommendations for leaders of co-production processes, with some recommendations for funders of projects adopting this approach. We have drawn on projects of various sizes, occurring over different timescales, motivated by a variety of reasons, and catalyzing a range of outcomes documented at different stages in the intervention process.

Preparing for co-production. Improving practices for co-production starts at the codesign phase, as this sets the foundations for the process, and is a critical time for problem framing,

Table 3 Reported outcomes from co-production processes

Stage	Outcomes from co-production	Reported examples
Improved process (approach)	Redistribute power	Changing the balance of power in traditionally hierarchical relationships by empowering marginalized groups, ranging from fishers in Bali (114) to mental health patients (115) to citizens not typically involved in the provision of water and sanitation services (76)
	Allow for creativity in generating new ideas and reframing problems	Increased creativity through engagement between researchers and practitioners in the codesign phase to create a knowledge network for enabling transformation in the field of sustainability (116).
	Encourage reflexivity	Medical professionals reviewed how medical services are offered to the medically underserved (117)
Proximate outcomes	Expand knowledge base and issue awareness	New collaborative data collection processes achieved between academics and practitioners (99), new knowledge about water governance (74), increased understanding of flood risk by vulnerable communities (81), and increased politician and citizen awareness of urban warming such that it became a tractable political issue (96)
	Increased capacity due to inclusion of users	Developing or strengthening interpersonal bonds and relationships (111, 120), such as between community members involved in a project to improve dementia management (125). This can lead to increased commitment to participate in co-productive processes, as with citizens who were willing to engage in urban planning processes (99).
Intervention outcomes (changes at multiple scales)	Improve well-being of individuals	Processes that shift individuals' perspectives on the problem or their perspectives on other actors (77, 106); building relationships between individuals (99, 125); and expanding individuals' capacity to contribute to a solution (114, 115). Increased empathy and understanding between individuals from different backgrounds was reported, especially in the health sciences (106, 110, 128) but also in sustainability-related projects (77). Such empathy improves the capacity of individuals who typically fill the role of providing services or knowledge to understand the needs and perspectives of their users.
	Improve products and service delivery	Improvements to environmental management practices (129) include increased adaptive capacity in Arctic communities (130), disaster preparedness of communities in Nepal (81), and the establishment of adaptive management of climate change monitoring in a rural community in Tanzania (77). Examples of improved public services include improvements in community safety (131), mental health services (115), solid waste management (132), and access to culturally appropriate services (133). Products created through co-productive processes range from adaptive capacity indices (130) to a mobile application for patients with hypertension (134) to maps inclusive of both scientific and local knowledge (81).
	Change knowledge systems (policy, institutions, funding)	Processes that establish long-term changes in relationships beyond a single co-production intervention (72, 87, 97, 135, 136). These efforts sought to influence the relationships between science, policy, and practice that defined existing institutional arrangements generally by establishing new institutions or major systems within institutions (97), forming new partnerships (72, 87, 135), or establishing new processes for integrating science and policy (136).
	Constructive interaction with cultural, historic, and societal norms	Studies that use the STS idiom to reframe relationships between state and citizen, science and society. For example, to highlight maladaptive policies and practices related to protecting communities vulnerable to landslides (89). Alternatively, the idiom has been used to articulate how academic concepts move into practice where there is alignment with cultural and social norms (95). Meek (93) applied the co-production idiom to design environmental education programs in Brazil to show how developing students' critical thinking about nature-society relationships can facilitate a societal transition from large-scale industrial agriculture to agroecology. Mahony (91) used the idiom to explain the response of the Indian government to the findings from the Intergovernmental Panel on Climate Change

relationship building, and the development of expected outcomes and means to realize them (47, 116). Before entering into a co-production process, the intended outcomes of an intervention should be made explicit and a group should critically assess whether or not co-production is an appropriate means to realize these outcomes in a given context (28). Even at this early stage, one must pay attention to how social and cultural norms, existing policy and institutions, and past relationships between communities, stakeholder groups, and organizations shape the interactions between individuals participating in the process (see green arrows in **Figure 1**). The following are important during this phase:

- To the extent possible, ensure representation from all relevant stakeholders, with attention to culturally appropriate participants (e.g., elders in some indigenous communities) and to empowering typically marginalized groups (89, 115, 137–139).
- Carefully consider which actors to engage, engage them early, and maintain their involvement throughout the process (101, 135, 137, 139, 140).
- Ensure that engagements are purposefully and strategically designed to meet a specific goal in support of project aims and objectives (28).
- Secure a facilitator for the process (109, 116, 141).
- Create relationships between actors that are horizontal rather than hierarchical, with leaders serving as facilitators or even as participants in the same activities as other actors (125, 141, 142).
- Consider the venue and meeting materials needed for the process (71).
- Be explicit about how decisions are going to be made, how responsibility and accountability will be shared, and how the process will be governed and managed (28).

Managing co-production. The proximate outcomes from an effectively managed co-production process can increase capacity of participants while expanding the available knowledge base to address a problem (see **Figure 1**). This stage of the co-production process received the most attention within the literature, leading to several lessons focused around the three key elements, (*a*) logistics—how to navigate meeting goals, content, and agendas, (*b*) relations—managing dynamics at the individual scale, and (*c*) capacity—the resource and physical needs of participants:

- Ensure that the process is open and flexible, invites frequent participant feedback, and facilitates learning (74).
- Establish clarity in actor roles, overall process, and timelines at the start using feedback from participants (143).
- Encourage diverse participants to take on others' perspectives (134).
- Identify appropriate decision tools and boundary objects to support the process (102).
- Focus on broad, cross-cutting issues relevant to all participants (116, 144).
- Carefully consider the effects of power dynamics between individuals and organizations on the process (e.g., potential frustrations and discomforts for participants) (87, 106, 134, 145).
- Where possible, ensure sustained resources and capacities, including venues, tools, and funds (71, 102, 108, 146).
- Designate funds for coordination, partnership support, dissemination of information, and encouraging action (108).
- Create funding incentives that foster creativity, as done in the arts (116).

Sustaining co-production. Achieving the desired outcomes of a single co-production intervention is challenging, but too often these difficulties eclipse an even bigger concern—securing a lasting impact within the broader social or political context. Co-production processes coevolve

within a broader set of institutional and cultural relationships (88, 95); every intervention is situated within multiple societal scales, and is influenced by social and cultural norms. Failure to account for the institutional context in which a given intervention is situated may result in ostensibly successful projects meeting a dead end when it comes to creating lasting change. Polk (99), for example, reports on a successful transdisciplinary process where diverse actors from across sectors generated new knowledge, but found that there was then no clear "home" for this new information because of the siloed nature of existing institutions. Interventions may need to strike a balance between adjusting to fit existing institutional arrangements and striving to change these arrangements to expand the realm of future possibilities (see arrows in **Figure 1**) (46). The following recommendations may assist those wishing to account for institutional context and sustain long-term changes in societal systems:

- Establish relationships between actors to consolidate relevant knowledge and catalyze new partnerships that may inspire future collaborations (72, 87, 97, 135).
- Explore options for continuing efforts beyond the budget and timeline of a single project, such as creating cross-scale and cross-sector partnerships to embed co-productive processes within existing structures, seek multiple funding sources, or link multiple projects together (72, 99, 135, 144).
- Unbundle desired services to determine where co-production would and would not be helpful (147).
- Ensure clear information and means of communication between local centers of power and higher-level supporting institutions (138).
- Give explicit attention to the pre-existing institutional context and relational preconditions for co-production; consider identifying scales relevant to the issue being addressed, and accounting for existing managerial routines for service or product delivery before creating entirely new approaches (146, 148, 149).
- Align funding priorities with the realities of co-production by changing incentives (e.g., encourage creativity) and focusing on real world impacts (71, 99, 106, 116, 144).

Navigating constructive interactions with society and culture. The final set of recommendations come primarily from scholarship employing the STS idiom of co-production. These suggestions consider the following ways in which the idiom can be used to account for the broad-reaching social and cultural norms that underlie knowledge systems, interventions, and even interactions between individuals:

- Recognize science as culturally situated and knowledge co-production (and the changes it may imply) as inherently political (76, 88, 95).
- Draw on the co-production idiom to (*a*) articulate power relations between participants and other actors to align with or challenge these dynamics as appropriate (92), (*b*) reveal how different types of knowledge gain or lose power (90, 91), and (*c*) design environmental education curriculums to facilitate societal transitions toward sustainability (93).

Taken together, although STS theory has focused on the potential analytical value of the co-production idiom, these studies offer the recommendation that the perspective be actively used by leaders and participants in the midst of co-production projects in sustainability sciences, and managed to illustrate what it might look like to do so (e.g., (90, 93). This lays some groundwork for co-production in sustainability science and action to more intentionally incorporate the co-production idiom, and thereby design more reflexive approaches to interventions in the future.

Implementation of best practices are, in themselves, insufficient to address some of the more intractable and political tensions that co-production processes struggle with when seeking to achieve the normative ends of social and political change. This is in part due to the nature of trying to bring about change for sustainability, which inherently involves disrupting the status quo and redistributing risks, costs, and benefits. Entrenched interests, institutions, and structures often benefit more powerful actors in society, and many proponents of co-production side with less powerful ones to counter this tendency. Instigators of co-production processes should be cognizant that it commonly requires reflexive practice and a significant commitment of time and resources, and even the most strenuous efforts will not always guarantee positive outcomes. Learning to undertake successful co-production interventions is an iterative process; the suggestions presented below offer a contribution to this learning process through a cross-fertilization of lessons learned across the two fields of sustainability science and public administration.

SYNTHESIS AND FUTURE DIRECTIONS

By empowering groups and or perspectives that are not traditionally engaged in knowledge production or decision making, co-production processes are generating new ways of thinking about and engaging with sustainability science and action. This rich history of co-production theory and practice from across sustainability science, public administration, and STS points to the following insights and areas for future research (see also the Future Issues at the end of this article).

First, co-production interventions are situated within cultural and institutional contexts that shape how individuals and organizations engage with one another, and coconstruct rules, norms, and practices that shape interactions between science and society. Considering the nested conceptual framework of co-production, interventions focused on community or stakeholder scales dominate the literature leading to well-established principles of good practice discussed above. Recent literature abounds with claims that effective interventions have co-produced a wide variety of outcomes—new relationships, knowledge, institutions, practices, and policies. However, these interventions faced challenges stemming largely from cultural and institutional contexts that are unable to accommodate unconventional approaches to producing knowledge and making decisions that shift the locus of power/knowledge to a more diverse cross section of society. Despite these well documented challenges, there is less attention within the literature on how to engage more effectively with the knowledge systems and sociocultural contexts that shape how those interventions play out in practice, and how they enable or constrain the realization of project goals and the attainment of desired societal outcomes. Several interventions where actors attempted to integrate results into existing institutions, or to scale up co-production processes in society, found this post hoc process challenging (99, 135, 138). This suggests a need to consider strategies to integrate with, or change, societal institutions proactively, rather than reactively focusing on strategies for integration after a project is completed.

Second, it is evident that STS observations about the inherently political nature of relationships among science and society are filtering into discussions of co-production within sustainability science. Bringing together diverse perspectives and empowering marginalized voices through co-production explicitly challenges the dominant views of expertise and how different types of expertise are positioned relative to decision-making power. Nonetheless, the politics of knowledge within these interventions receives insufficient attention. There is a need to more readily ask the following questions: Whose expertise counts? How are participants selected to be part of these processes? What mechanisms are used to ensure that participants voices are actually representative of their constituents? How are different conceptions of knowledge embedded in the objectives of co-production processes? Additionally, how are different knowledge claims and perceptions of

evidence reconciled? Suggestions include ensuring that processes are designed to "open up" rather than "close down" debate about alternatives (33, 35), and considering the multiple social orders that are likely to be implicated in or affected by co-production processes (36). Given that these questions have been asked before (33, 34, 36, 46), we reiterate calls for greater engagement with the STS literature to provide a more coherent theoretical framework to conceptualize power within co-production processes, and conversely greater engagement from the STS community to provide practical guidance on how to engage with the inherent politics of co-production interventions.

Third, the various outcomes identified here support claims that co-production processes are leading to tangible outcomes, despite questions otherwise (20, 26, 28). However, this review (and indeed the broader literature it draws on) does not enable us to attribute causality between elements of a process and a particular outcome. As such, we reiterate calls for a greater evidence base to examine whether the promise of co-production is realized through its practice. The interdependence of variables makes it difficult to systematically compare cases, or parse out the importance of different aspects of co-production as they appear to work iteratively and synergistically. Given the varied interpretations of the concept, the number of ways it is practiced, and the diversity of settings in which it is applied, it is also rarely possible to evaluate counterfactuals (e.g., what would have happened in the absence of a co-production approach) or attempt different interventions across similar contexts. These challenges suggest a growing need for conceptual and empirical work to examine the assumptions underpinning claims about the societal benefits and impacts of co-production. This will need to be paired with more dedicated time and resources to monitor and evaluate co-production processes using shared frameworks that enable cross-case and cross-sector comparisons.

Fourth, if ad hoc implementation of co-production interventions is indeed leading to "better outcomes," this suggests that public policy for sustainable development could create institutional frameworks and incentive structures that encourage greater uptake of co-production practices. For example, there is some indication that embedding co-production into broader institutions can create impacts that extend beyond the site of a particular intervention (72). Current scholarship from public administration offers a range of examples to consider how to incentivize co-production within public policy for sustainable development. Many of the cases within health services specifically reported on projects that had taken place within the context of broader policy shifts to support co-production. Further investigation of such shifts in national or regional policies could provide fruitful lessons for sustainability science and action. This could start by reconceptualizing sustainability as a public good, and co-production an approach to delivering sustainability services and then examining how such service delivery is embedded within existing practices, policies, and institutions. Critically drawing on this literature will enlarge the focus beyond how to collectively produce knowledge, toward how to change the broader societal processes for making decisions about sustainability.

Finally, current scholarship predominantly reports on cases of "successful" co-production, despite acknowledged challenges and limitations. Reporting on failures, tensions, and trade-offs related to both processes and outcomes of co-production is needed to genuinely progress theory and practice. Discussion of such challenges could usefully be situated within a broader effort to address the lack of accountability mechanisms available for sanctioning poor behavior or unmet promises made to societal stakeholders by the research community (37). Furthermore, there is a need to move beyond novel and ad hoc processes and blanket calls that this is how research "should be done" to a greater appreciation of when co-production is the "right approach" (28) and then to develop institutions that facilitate the practice when this is the case. A greater appreciation of contexts in which co-production processes "failed" will further understanding of when not to pursue this approach.

CONCLUSION

The broad theoretical and empirical material of this review makes clear that co-production processes have a role to play in charting pathways to sustainability. Effective co-production processes actively link scientific and other knowledge with values to develop visions and goals for the future. However, producing knowledge is not enough; rather, outcomes must be realized through enacting strategies for change. To ensure lasting change these strategies also need to influence the evolution of institutions, build capacity to produce and use knowledge, and facilitate relationships between researchers and other societal actors. As such, this review focused on beginning to flesh out how to move beyond simplistic ideas of matchmaking "scientists" and "decision makers" to solve sustainability problems, toward a more sophisticated and nuanced approach to co-production. If the co-production of knowledge within sustainability science ultimately hopes to alter existing institutions, actors must see their work as an endeavor to change existing science-society interactions. That said, it is always worth critically examining the design choices one is making in choosing to co-produce science and governance in one way versus another. Different contexts and different problems require very different approaches to co-production. Further investigation into which co-production designs work well under which circumstances—drawing on both successes and failures—is needed to develop a more robust understanding of the utility of this approach in bringing about systemic or institutional change.

This transition in how to approach co-production within sustainability science begins with the STS proposition that efforts to co-produce knowledge are an exercise in constructing social order. Consequently, who participates, how they are engaged, and whether their knowledge and perspectives have a legitimate place, matters (10, 34). This can be addressed through mechanisms that articulate the governance of co-production processes, from which there is a rich history of theory and practice within public administration to draw. The theoretical contributions of STS and public administration scholarship provide key insights into why simplistic calls for communication and collaboration between scientists and stakeholders may fail to deliver on the promise of "improved" decision making; how interventions designed without thorough understanding of the context, culture, and actors at best struggle to meet their goals, and at worst have significant negative impacts; and the processes and capacities that are more likely to lead to the desired outcomes of co-production. Calls for scientists and science agencies to engage more transparently and openly in debates about the values that underpin how we make decisions about sustainability challenge the notion that science should be objective and value free. Thus, realizing the promise of co-production will also require individual scientists to critically reflect on, and be open about, their role in advocating for social and political change.

SUMMARY POINTS

1. Co-production offers a framework to integrate diverse perspectives and knowledge into decision making and action for sustainability.
2. Theory and practice across public administration, science and technology studies (STS), and sustainability science should provide a holistic picture of the processes, mechanisms, and capacities required to undertake and institutionalize co-production practices for sustainable development.
3. Co-production processes should be conceptualized within a nested framework that connects individual actors and interventions into broader institutions, governance systems,

and sociocultural norms that shape how knowledge is produced and decisions about sustainable development are made.

4. Principles of good practice for designing and managing co-production interventions are well established within the literature; however, there is a need to further develop theoretical and practical insights into how to intervene in broader systems and sociocultural norms to bring about necessary cultural, political, and institutional change for sustainability.
5. Co-production does not uniformly lead to "better outcomes." Instigators of co-production processes should be aware of the time and resources required to genuinely engage in collaborative processes, and are cautioned to examine whether these means are the most effective way to realize a given end. Furthermore, they should be encouraged to acknowledge how their own worldviews and assumptions are externalized in pragmatic design choices and catalyze certain pathways down the co-production pathway.
6. Co-production is an inherently political act, as it seeks to connect what we know about a problem with policies and actions that seek to change how that problem is addressed. This requires individuals and organizations engaged in these practices to acknowledge their role in motivating social and political change and attend to the tensions and trade-offs therein.
7. There is a greater need to engage with the politics of co-production to consider whose knowledge counts, how participants are selected to be part of co-production processes, what mechanisms are used to ensure that participants voices are "representative" of their constituents, how are different conceptions of knowledge embedded in the objectives of co-production processes, and how are different knowledge claims and perceptions of evidence reconciled.

FUTURE ISSUES

1. Future research should address the institutionalization of co-production, whether through scaling up by mainstreaming co-produced decision-making frameworks within government agencies, businesses, etc., or through policy mechanisms that encourage/enable co-production at intervention scales.
2. Systematically investigate the design of interventions that affect embedded knowledge systems and empirically articulate examples of knowledge systems that facilitate co-production processes.
3. Further develop a conceptual framework that engages with both theory and practice and articulates the nested scales of co-production to examine the role of cross-scale interactions and how this can usefully support practice.
4. Engage the STS literature as an entry point to systematically conceptualize the normative and political dimensions of co-production interventions within sustainability science, and to develop practical recommendations for how practitioners can engage with the politics of co-production interventions.

5. Investigate the extent to which individual co-production interventions are changing existing policies and institutions, as well as the broader social and cultural norms that shape science-society relations within a given geography or thematic issue.
6. Develop and apply shared frameworks to monitor and evaluate the diversity of intended and unintended outcomes being realized through co-production processes.
7. Develop a more robust understanding of which types of co-production practices are effective, and under which circumstances, and develop heuristics that can be used to guide instigators of co-production practices to determine which practices are appropriate for a given context or problem.
8. Investigate, compare, and communicate failures, tensions and trade-offs related to both processes and outcomes of co-production.
9. Develop a more nuanced appreciation of how to utilize different types of co-production practices in different contexts and for different types of problems.

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