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Advancing co-production for transformative change by synthesizing guidance from case studies on the sustainable management and governance of natural resources

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ABSTRACT

Co-production has become paramount for scientists, practitioners and social groups of Indigenous peoples and local communities of rural and urban areas to deliver transformative changes that enhance sustainability. Co-production should result in knowledge that is credible, legitimate and usable to enable sustainable outcomes effectively. However, this is not always the case due to challenges related to differences between scientific and Indigenous and local knowledge, as well as inherent power imbalances. The literature emphasises that these challenges are often triggered by rigid scientific theories and postures, dominant practices, and time-money limitations that co-production projects involve. This happens despite the adoption of guidelines recommended in the literature. We investigate the role of these challenges and guidelines in the generation of credible, legitimate, usable, and effective knowledge. We analyse this role in 13 co-production cases focused on sustainable transformative changes linked with the management and governance of natural resources across the globe. Despite challenges varying between groups and contexts, credibility, usability, and effectiveness are promoted simultaneously, especially when co-production empowers social actors via legitimate processes. Scientists and practitioners do so, through creative and flexible reshaping of existing knowledge and worldviews with a focus on common goals that link sustainability and livelihoods. They conceptualise a mutual understanding of knowledge and that is deemed trustworthy feasible to use in their socioecological context. Our findings complement existing scholarship on co-production, exploring the credibility of situated knowledge and its practical effectiveness together with its commonly addressed legitimacy and usability. A focus on the practices

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of different actors, including dynamics that are external to co-production, and changes in the scientific and social *status quo*, are needed to advance co-production effectiveness.

1. Introduction

The collaborative production of knowledge and practices (co-production) is inherently part of participatory or transdisciplinary research and projects that span science, policy, and social interfaces (Tengö et al., 2017; Chambers et al., 2022). Co-production is used to include both scientific knowledge and 'Indigenous and local knowledge' systems (ILK) (Díaz et al., 2015) in several activities, for instance project design (Wheeler & Root-Bernstein, 2020), environmental assessments (Sutherland et al., 2017) and planning (Matuk et al., 2020). Such activities aim for transformative changes through which 'Indigenous Peoples and Local Communities' (IPLCs) improve the management and governance of natural resources and mitigate environmental problems such as climate change and loss of biodiversity (Wyborn et al., 2020). For example, in a project related to 'Reducing Emissions from Deforestation and Forest Degradation' (REDD+), Indigenous peoples co-produced an assessment with practitioners to ensure that local livelihoods were not jeopardised by efforts to reduce deforestation (Amaral et al., 2021). In another example, scientists and local citizens planned to improve the selective collection of solid waste to reduce biodiversity loss resulting from pollution (Rada et al., 2020).

In this study, we draw upon various scientific fields that address sustainability literature (Tengö et al., 2017; Chambers, 2022) – i.e., Science and Technology Studies (STS) (Wyborn et al., 2019, 2020), participatory (action) research (Freire, 1996; Almekinders, 2009;); ethnoecology, ethnopedology (Toledo and Barrera-Bassols, 2009), ethnobotany (Albuquerque et al., 2014), citizen science (Bonney et al., 2009), circular economy (Marra et al., 2018), postcolonial (Latulipe and Klenk, 2020), and feminist studies (Sato and Alarcon, 2019). We stipulate that to be effective, co-production should result in knowledge that is credible, legitimate, relevant, usable and accepted for all involved. This includes scientists, practitioners (e.g., actors who work with policy or non-governmental organisations (NGOs)), and IPLCs. By credible and legitimate, we refer to the co-produced knowledge that all these actors accept as trustworthy and inclusive (see Cash et al., 2003a, 2003b; Matuk, 2020; Schuttenberg and Guth, 2015). By relevant, we mean that this knowledge is theoretically and practically fit to address the actors' needs within the social-ecological context in which co-production is addressed. Finally, this knowledge is accepted by actors when it enhances the sustainability of the impacts and outcomes in practice (cf. Matuk, 2020). This knowledge improves the understanding of how to manage resources more sustainably and increases the chances that IPLCs will endorse transformative changes together with other actors (Hansson and Polk, 2018). Therefore, it creates space for these actors to move beyond the exclusive recognition of the credibility and usability of scientific knowledge and challenge epistemic inequalities grounded in colonial hierarchies among actors (Latulipe and Klenk, 2020). It also invites them to be critical of co-production processes and uncertainty of it leading to ecological sustainability in practice (Brix et al., 2020).

While knowledge credibility, legitimacy and usability (CLU) are central to co-production effectiveness, its achievement is often challenged by knowledge differences that exist between and within different knowledge systems, and by power imbalances among knowledge holders (Turnhout et al., 2020). These differences relate to epistemologies (how to know), ontologies (what is there to know) and associated axiologies (values support what and how we know) (Woolgar and Lezaun, 2013; Ludwig and El-Hani, 2020), which may be reflected in differences in problem conceptualization, classification categories, needs, goals, worldviews, values, beliefs, and interests. For instance, different groups of scientists and local communities may differ in how they respectively validate land use indicators they know and use towards achieving their goals. These differences might be, in some cases, hard to reconcile during co-production processes of bringing knowledge systems together – i.e., mobilizing (exchanging, bringing out, selecting), weaving (bridging, braiding, combining), translating (into a common language of communication, and synthesizing (reframing) commonly accepted knowledge (Tengö et al., 2014, 2017). In turn, power imbalances constrain this reconciliation (Matuk et al., 2020). These imbalances originate from scientists and practitioners who usually hold more power than IPLCs to influence what knowledge is adopted or implemented for change (Agrawal, 1995; Turnhout et al., 2020). Therefore, scientists tend to engage with IPLCs and their ILK in a hierarchical manner, believing that science is better equipped to solve problems.

Challenges related to knowledge differences and power imbalances during co-production processes are largely ascribable to the rigidity of theories and postures and to dominant methodological practices (Matuk et al., 2020b; Simon et al., 2018; Turnhout et al., 2019, 2020). Moreover, time-money limitations that are common in co-production projects serve as another major challenge (Lemos et al., 2018; Chambers et al., 2022). The literature recommends practical guidelines for the co-production actors to adopt towards overcoming these challenges: 1) reciprocal engagement and flexibility; 2) mutual understanding and deliberation; and 3) trust and creativity (Tengö et al., 2017; Matuk, 2020; Chambers et al., 2022). (Ayana et al., 2015; Matuk et al., 2020b). For example, the premises of scientists and rigid formality can prevent the participation of IPLCs in participatory methods, making it difficult to develop mutual understandings to reconcile knowledge differences. Additionally, much of what is proposed in these guidelines comes mainly from scholars from the global South and to some extend from the scholars from the global North. Meaningful engagement with IPLCs and ILK remains mostly absent in the literature focussing on the practice of co-production (Turnhout et al., 2020). Finally, the time-money limitations of co-production processes tend to limit the space for actors to identify and engage more deeply with knowledge differences. This may lead to scientists and practitioners dominating co-production decisions during project design, environmental assessment and planning with IPLCs. This is done to pursue project planning and project activities needed to meet project objectives (Meehan et al. (2018); Cockburn et al. (2017)). The outcome is an extraction of ILK, used and interpreted to match scientific data, yet detached from the meaning and use it has for IPLCs (Klenk et al., 2017). These outcomes lead IPLCs to question the CLU of the knowledge generated and to hamper its effectiveness. This indicates the need for studies that help to understand the role of these challenges and guidelines in co-production and how they affect co-production effectiveness (Díaz et al. (2018); Djenontin and Meadow (2023); Wyborn et al. (2020); Wheeler and Root-Bernstein (2020); Matuk et al. (2020b)).

We investigate the role of the aforementioned challenges and guidelines in co-production. Specifically, we explore whether and how these guidelines enable actors to overcome these co-production challenges and achieve knowledge CLU and effectiveness. We do so by applying a conceptual framework to 13 diverse cases of co-production from around the globe. We explain the selected cases in Section 3, but different types of IPLCs – urban citizens; modern and traditional farmers (or peasants), traditional communities that rely on customary practices aimed at subsistence and Indigenous peoples. In this context, we contribute to the flourishing scholarship on co-production in two main ways. First, the existent literature focuses on the legitimacy and usability of co-produced knowledge, which involves a debate on the credibility of this knowledge for different actors and on its effectiveness (Lemos et al., 2018; Díaz et al., 2018; Wagner et al., 2023). We complement this literature by exploring the emergence of the knowledge attributes CLU and their role in the 'effectiveness' of co-production. Second, we enrich existing literature that theorises on practices that help scientists to tackle knowledge differences and power imbalances with society (Tengö et al., 2017; Turnhout et al., 2020) with an exploration of how this occurs in practice. These contributions enable us to share insights on principles and practices that help advance the effectiveness of co-production.

2. A conceptual framework to assess knowledge credibility, legitimacy, usability, and effectiveness

Our conceptual framework draws on 'CLU' and 'effectiveness' as the core attributes of knowledge. We understand legitimacy as resulting from the perception that the production of knowledge or information has been respectful of "*divergent values and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests* (Cash et al., 2003a, p. 8087)." Credibility refers to the validity and trustworthiness of knowledge (Cash et al., 2002, 2003; cf. Schuttenberg and Guth, 2015). Usability refers to the relevance and appropriateness of applying knowledge to address actors' needs and contexts (Cash et al., 2003b; Clark et al., 2016; Lemos et al., 2018). While explaining usability, Cash et al. (2003a), (2003b) focus on salience which they explain relates to whether mobilized knowledge address the problem central to coproduction. We apply a broader framing for the concept of usability to emphasize that this knowledge should be relevant and fit to address the needs prioritized by the various actors in terms of feasibility, practice, and social-ecological context (cf. Matuk, 2020).

CLU are often entwined, linking knowledge and action or practice. They are thus considered to affect the effectiveness of co-produced knowledge. Effectiveness refers to knowledge and co-production that generate social and environmental impacts or outcomes; specifically, when knowledge is adopted in practice to enhance sustainability (Matuk et al., 2020b; Lemos et al., 2018). The problem is that holders of different knowledge systems can have different interpretations of the knowledge that bears CLU (Wheeler and Root-Bernstein, 2020). In the attempt to inform social practices with information that scientists and practitioners consider credible (according to science), they often compromise the legitimacy and usability it has for IPLCs, thus reducing its effectiveness (Turnhout et al., 2020). We assume that co-produced knowledge should have its CLU attributes evaluated by different actors participating in co-production in a non-hierarchical manner that is shaped according to the situated context of its application. This knowledge should enhance the effectiveness of actions and sustainable solutions (cf. Hansson and Polk, 2018; Matuk, 2020; Leino and Peltomaa, 2012). We recognise these definitions are based on scientific concepts, and may be counterpoised in co-production involving actors that draw upon other knowledge systems.

We consider the way knowledge holders characterise, validate and use knowledge should be subject to reflection during co-production (Matuk, 2020; Hill et al., 2020). For instance, many scientists portray their systems of classifications and conceptualizations as being neutral from ontologies and universally applicable (Bowker and Star, 2000; Woolgar and Lezaun, 2013). Nevertheless, other scientists recognise that research design involves subjective choices and that the experiential knowledge of scientists interferes with research processes and findings (Collins, 2001). Scientists usually identify CLU when knowledge is produced following systematic empirical methods and is published in peer-reviewed outlets (Cash et al., 2003b). Practitioners also have scientific knowledge, although the literature stresses their technical and professional knowledge. However, scientists and practitioners with a background in social and natural sciences validate knowledge using different qualitative and quantitative methods (Turnhout et al., 2019).

In accordance with the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), we define that ILK includes diverse knowledge systems and is "*a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment. It is also referred to by other terms such as, for example, Indigenous, local or traditional knowledge, traditional ecological/environmental knowledge (TEK), farmer or fisherman knowledge, ethnoscience, indigenous science, folk science* (Díaz et al., 2015, p. 13)."

We emphasise that ILK systems differ from each other in some respects and vary within their own domains, which implicates that each approach and methodological process used for co-production needs to be adapted not only according to the type of knowledge but also to each case and context. Overall, Indigenous knowledge is inseparable from Indigenous practices and holistic ontologies. It is orally transmitted via storytelling, music, and traditional practices (Parsons et al., 2017; Latulipe and Klenk, 2020). It is intricate to long-term relations to the lands of these original inhabitants of global areas and to animist values and worldviews, also referred to as cosmologies (Scoville-Simonds, 2018; Man Han Chit Htoo et al., 2022). These worldviews imply that animals are spiritual and intelligent entities from whom Indigenous peoples learn and have ethical obligations to (Man Han Chit Htoo et al., 2022). Shamans and local cultural leaders are influential in knowledge transmission, but communities also validate knowledge based on their values, morals, needs, and circumstances (Lickers, 1997). Although Indigenous knowledge is rooted in traditions, its holders adapt it in response to environmental change (Hitomi and Loring, 2018). Concurrently, Indigenous knowledge varies with Indigenous ethnicity and context (Nascimento and Vieira, 2015; Matuk, 2020). Additionally, co-production with Indigenous peoples must take into consideration aspects related to identity, land, and intellectual rights, and to cultural heritage as recognised by international treaties and national laws (e.g., Mauro and Hardison, 2000; Cittadino, 2019). Co-production must also contemplate the benefit sharing arising from the utilization of Indigenous knowledge (see Nagoya Protocol of the CBD; Wright, 2020).

Finally, despite the fact that the groups holding local knowledge vary considerably across the globe, studies indicate that the adoption of co-produced knowledge depends on it meeting their values, needs, and contexts (Klenk et al., 2017; Matuk et al., 2017, 2020a). Specifically in the Global South, co-production often addresses peasants and citizens who draw their knowledge mostly from place-based experiences and values (Freire, 1996; Coelho, 2014). Co-production also addresses traditional communities (e.g., formed by marooned escaped slaves or tappers) who base their knowledge on multigenerational land use and holistic ontologies, and on exchanges with IPLCs (Matuk et al., 2017). Yet, co-production with traditional communities must account for needs insufficiently covered by policies and often relating to the colonial histories in their lives (Santos and Meneses, 2010). Unlike in the Global North, co-production with Southern peasants often addresses citizens and modern farmers, who next to scientific knowledge usually rely more on situated and experiential knowledge (Strasser et al., 2019). Moreover, co-production with these groups should also elevate their needs and knowledge to be included in decisions that will affect their lives (Brix et al., 2020).

2.1. Challenges and guidelines that affect credibility, legitimacy, usability and effectiveness in co-production

The literature on sustainability and co-production emphasises that scientists, practitioners and IPLCs should use good practices to achieve CLU. We synthesize three key guidelines, associated with overarching triggers that make knowledge differences and power imbalances emerge during co-production processes (Fig. 1).

Below, we exemplify how the triggers manifest and we point at possible strategies to deal with knowledge differences and power imbalances, based on the three guidelines of our framework.

1) Rigid theories and postures: Reciprocal engagement and flexibility to reshape.

The rigidity of the premises of scientists and practitioners reinforces pre-existing power structures. This limits the ability of scientists and practitioners to elicit and understand ILK and IPLCs perspectives (Chambers et al., 2022; Turnhout et al., 2020). Furthermore, it inhibits their ability to make sense of knowledge differences between IPLCs and their own scientific knowledge. For instance, a disciplinary approach to address IPLCs may prevent them from meaningfully engaging in co-production as their knowledge is holistic and as such requires an interdisciplinary approach (Matuk et al., 2020). Scientists and practitioners strive to move beyond these structures and premises when they empower IPLCs to reshape pre-given concepts, classifications, and models. They do so by developing a reciprocal engagement with IPLCs and being flexible to do this reshaping (Wyborn et al., 2019). For example, scientists being transparent when explaining the objectives of their project and the purposes of their methods. Another example is scientists embracing a plurality of values and knowledge that enforce sustainability (Kenter, 2018). This guideline is followed when all actors, including scientists and practitioners: i) reflect and learn from tensions or insights, to reshape their postures (Klenk, 2018); and ii) change the *status quo* of their practices towards supporting changes in the sustainable management and governance of IPLCs (cf. Chambers et al., 2022).

2) Dominant methodological practices: *Mutual understanding and deliberation*.

When scientists and practitioners dominate the steering of co-production, they may generate unintended (uncontrollable or performative) dynamics that compromise knowledge CLU (Turnhout et al., 2020) - e.g., when they lack facilitation skills. However, they can also negotiate and reframe methods with IPLCs to develop mutual understandings of knowledge differences (i.e., correspondences and complementarities between concepts, classifications and goals) and deliberate on changes that enhance sustainability with them. One possible strategy is that they can help IPLCs bring out ILK, and decide together on distributional justice aspects (who decides and benefits from decisions). The use of this strategy is detectable when actors: i) rely on boundary objects – e.g., livelihoods (Clark et al., 2011); ii) make inter- and transdisciplinary efforts to grasp the reasons behind knowledge choices (Lélé and Norgaard, 2005; Ingold, 2011); and iii) 'inherit' or appropriate elements of each other's knowledge (Meehan et al., 2018). For example, scientists accept the sacred value that locals attribute to lands where their ancestors are buried as a credible or valid indicator to decide governance. The resultant outcomes of these processes combine knowledge systems allowing IPLCs to recognise ILK, and align project goals and local needs (cf. Matuk et al., 2020b).

3) Limiting time and money resources: *Trust and creativity*.

The lack of time and material resources reflects the structural limitations of academia and commodified research that underfund co-production while putting emphasis on competition between its actors, including IPLCs. The same limitations are found in projects of policies and NGOs that address co-production with IPLCs. Although these limitations require structural responses, scientists are challenged to mitigate them by cultivating trust and creativity. Participatory processes take time and money – e.g., to organize and carry out meetings, build trust, and achieve a shared understanding of ILK (Lemos et al., 2018). Often, scientists and practitioners do not limit their own space. This goes at the expense of the voices of IPLCs and ultimately sharing power, for instance when selecting the criteria for water governance (Oliver et al., 2019; Wyborn et al., 2019). Studies also show that when scientists and practitioners take a less rigid approach towards IPLC and invest in building trust this optimizes time and money (Evans, 2006; Matuk et al., 2019, 2020a). They do so by readjusting research methods and objectives to the local needs and goals of all actors involved. Trust is often identifiable when project activities ensure the participation of IPLCs. In turn, creativity is tangible when the development of creative solutions minimises these limitations and enables lower-cost changes (Matuk et al., 2019). For instance, trust and creativity reduce constraints to time and costs when different researchers facilitate different fieldwork activities simultaneously or adapt their interviews and workshops to incorporate ILK-related information and methods proposed by IPLCs.

The suggested guidelines can enable co-production to generate knowledge CLU, thus yielding the foundation for effective changes related to natural resource management and governance carried out by IPLCs.

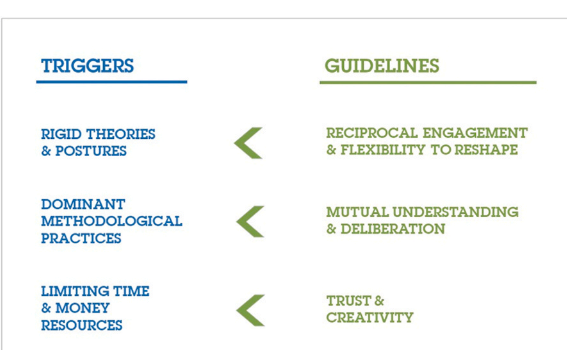

Fig. 1. Triggers related to challenges of knowledge differences and power imbalances with guidelines for actors to address them.

3. Material and methods

The location and characteristics of our 13 study areas are presented in Fig. 1 and Table 1. Four of these cases addressed Indigenous peoples and nine of them addressed local communities, of which four included rural participants and five included urban or mixed groups.

3.1. Data collection and analysis

Following applicable local and/or international protocols, we present the free and prior informed consent and the ethical procedures used for data collection in Table 1. In addition, Fig. 2 illustrates data collection across research fields, methods, and IPLC and other groups in specific cases. The first author invited the co-authors to contribute data based on case studies and publications. This enabled an analysis across common characteristics but also delivered a variety of aspects for broader reflection on co-production processes and effectiveness. The cases were selected from scientists that actively facilitated the co-production of environmental assessments and planning processes with the participation of IPLCs, NGOs and/or policy practitioners. The intention was to generate credible and legitimate knowledge for implementing sustainable transformative changes in the management and governance of natural resources.

Qualitative data analysis was carried out through two rounds of 'thematic coding' (Nowell et al., 2017) of data from the different cases such as notes on fieldwork activities; recorded and transcribed interviews that had followed a different structuring pertinent to each project. The first author guided the co-authors in gathering and synthesizing data from their respective research via e-mails and online dialogues. She structured the data (based on the headlines of Fig. 1 and Table 1) in order gather similar information across cases needed for comparative analysis. Overall, this information focused on: 1) how co-production was facilitated; 2) how co-production decisions prioritised and included research framing, assessment, planning and data analysis – e.g. problem conceptualizations, classification categories and indicators, needs, goals, worldviews, values, beliefs and interests; and 3) whether and how co-production processes generated knowledge CLU and led to effective outcomes.

In each case, the form of participation of practitioners and IPLCs was classified as 'active' or 'informative' (Table 1). Active participation refers to actors adding their knowledge to co-production process and decisions; by evolving and aligning research methods with environmental assessment and planning activities. Informative participation refers to actors not participating or participating shortly in these decisions (cf.

Table 1
Projects, roles of actors, research field and form of participation, location, general characteristics and problems addressed in each context, and methods and activities involved in co-production. References cited in the research field relate to publications and projects that case studies have been derived from.

Project focus	Co-production: role of actors + participation (active/ informative)	Research field	Location	Social-ecological issue	Methods/activities & project duration
***With citizens* and local knowledge (LK).**					
1) *Establishing a program for selective solid waste collection*	Scientists (active): program design/planning and uptake Policy practitioners (active): program design/planning and uptake Citizens and Peasants (informative): Deployment of LK; knowledge exchange on waste management	Transformative research (Freire, 2017; Lam et al., 2020)	São João Evangelista in the Atlantic Rain Forest (Minas Gerais, Brazil)	Poor and polluted region with solid waste management issues and low levels of education level	4 Environmental campaigns in public spaces (130 people/average); 10 interviews - 1,5 years
2) *Searching for new pocket parks in Amsterdam*	Scientist (active): assess locations for small-scale green spaces Policy and NGO practitioners (active): co-producing indicators with scientists; facilitating process or urban greening; engaging citizens Citizens (informative): planning locations and implementation of parks	Urban greening, Citizen Science (Bonney et al., 2009)	Amsterdam (The Netherlands)	Growing urban expansion in an intensely used landscape causes declining green space and urban biodiversity loss combined with a need for climate change adaptation	2 Workshops; 4 focus groups; Geographic information science (GIS); 86 site visits by local citizens and practitioners - 2 years
3) *Updating the management of a cultural stream by citizens*	Scientists (active): mediate management update/ biocultural conservation Policy/Water Board practitioners (Hydrology, Ecology) (active): collaborative advise/ implementation Citizens (active): bringing in management history/practice and co-producing changes	Nature Conservation; urban greening, Ecology, Hydrology, Cultural History.	Driebergen (The Netherlands)	Citizens have managed a green space for 25 years, conserving a springwater system/greenblue infrastructure now under threat from climate change, dropping water levels and water quality	2 Workshops; 2 technical visits for ecological measurements; 2 joint walks to learn about, and plan management - 4 years
4) *Avoiding the harm from salt mining in the urban environment*	Scientists (active): mediating a safer measurement of mining impacts Policy/Ministry of Economic Affairs practitioners (active): support scientists and citizens Citizens (active): creating a new framework to measure mining impacts to be licensed Mining company (informative): collaborating to prevent harm	Environmental conservation, Cultural heritage conservation	Harlingen (The Netherlands)	Citizens prevent salt mining impacts in urban residential areas, i.e., loss of houses and heritage buildings under threat from soil subsidence	20 Interviews, participant observation - 4 years
5) 2000 m^2 *for sustainable agriculture*	Scientists (active): supporting practitioners with co-production Policy and NGO practitioners (active): engaging citizens in setting the course for the national transition to resilience/zero-carbon emission by 2050 Citizens (active): to adopt or improve agricultural sustainability; uptake healthy diets	Circular economy (Marra et al., 2018)	Kockelscheuer, Luxembourg City (Luxemburg)	Most citizens have unhealthy/ unsustainable diets and do not have a home garden. Most local farmers could produce more sustainably under climate change	2 Workshops (25 people/ average); 42 seminars in demonstration gardens/ agricultural sites - 3 years
***With farmers and traditional communities* and local knowledge (LK)**					
6) Advancing participatory research oriented to sustainability with agroecology	Scientists and graduate students (active): providing agroecological technical support Policy practitioners (informative): supporting peasants to increase food productivity and diversity while maintaining their sustainable practices Peasants (active): co-creating problem understanding and	Action research (Almekinders et al., 2009); Agroecology (Gliessman, 2001)	São João Evangelista in the Atlantic Rainforest (Minas Gerais, Brazil),	Poverty, low productivity, and low food diversity in the municipal food market	5 Workshops (30 people/ average); 24 interviews - 1 year

(*continued on next page*)

Table 1 (*continued*)

Project focus	Co-production: role of actors + participation (active/ informative)	Research field	Location	Social-ecological issue	Methods/activities & project duration
	solution, and raising income and sustainability				
7) Knowledge and power in transdisciplinary research with traditional fishers	Scientists (active): studying LK and enhancing mangrove biodiversity, learning together Traditional fishers (active & informative): reshaping LK, learning together and co-creating school materials	Participatory research (Chevalier and Buckler, 2013;Sato and Alarcon, 2019)	Siribinha in the Atlantic Rainforest (Bahia – Brazil)	Poor population; low policy support; balance conservation and livelihoods in the mangrove estuary	5 Workshops with participatory activities (12 people/average); ethnographic participant observation; 50 interviews - 4 years
8) Grape marc - From underrated waste to premium fertilizer	Scientists (active): mediating co-production of a pilot-project/strategy to close carbon cycles in the country Policy and NGO practitioners (active): implementing the 'Yes We Care' -program Winegrowers (active): co-creating the fertilizer and program	Circular economy (Marra et al., 2018)	Schwebsange in the Moselle River valley (Luxembourg)	Winegrowing region affected by climate change and carbon pollution that can become carbon storage in soils	14 Workshops (5 people/ average); demonstration site - 3 years
9) Reducing turtle bycatch in a small-scale fishery	Scientists (active): mediate bycatch mitigation, keeping fish livelihoods/trade Policy and NGO practitioners (informative): regulate turtle protection Fishers / fisheries managers (active): reducing/supporting the reduction of turtle bycatch	Participatory research on sustainability (Larocque et al., 2020), Biology, Social Sciences.	Eastern Ontario (Canada)	Biodiversity loss and livelihood dependency in a region of important turtle biodiversity involves turtle bycatch by fishers' hoop nets	2 Workshops (20 people/ average); 40 interviews conference calls - 4 years
***with Indigenous peoples* and Indigenous knowledge (IK)**					
10) Assessing the legitimacy and effectiveness of co-production to mitigate climate change with Amazon Kaxinawás	Scientists (active): analysing co-production Policy practitioners (active): providing technical support and SISA (REDD+) *Kaxinawás (active)*: problem understanding/solutions to rescue/enforce traditional practices/conservation	Ethnoecology (Toledo and Barrera-Bassols, 2009)	*Kaxinawá* Nova Olinda Indigenous Land in the Amazon Rainforest (Acre, Brazil)	Traditional IP activities (fishing, gathering, hunting, agriculture etc.) under pressure from climate change and deforestation. A return to REDD+ funds with a growing population puts pressure on biodiversity	3 Workshops, participatory mapping (35 people/ average); participant observation; 20 Interviews - 4 years
11) Reinforcing traditional food and medicinal practices with Amazon Kaxinawás	Scientists: helping locals conserve food practices and security/sovereignty Policy practitioners (active): providing technical support and implementing SISA (REDD+) *Kaxinawás (active)*: exchanging and rescuing traditional knowledge and practices	Ethnobotany (Albuquerque et al., 2014)	*Kaxinawá* Nova Olinda Indigenous Land in the Amazon Rainforest (Acre, Brazil)	Important agrobiodiversity foresees in the growing consumption and demand of urban food	60 Interviews, 35 technical visits to home gardens/ crops, including participant observation; several guided tours/cataloguing IK - 4 years
12) Conserving ecosystem services, agrobiodiversity and human health with Amazon Puyanawas	Scientists (active): supporting practitioners and *Puyanawas* Policy and NGO practitioners (active): technical support and implementation of SISA (REDD+) *Puyanawas (active & informative)*: assessing soils/ natural resources and planning practices to enhance sustainability/health	Ethnopedology; Ethnobotany (Albuquerque et al., 2014)	*Puyanawa* Indigenous Land in the Amazon Rainforest (Acre, Brazil)	Growing population induces urban food consumption which causes health issues and pressure on biodiversity	4 Workshops, demonstrative gardens, participatory mapping (8 people/ average), 10 Interviews - 4 years
13) *Wildlife management with Airumakuchis in the Colombian Amazon*	Scientists (active): understand the role of local governance norms and IK on wildlife management sustainability CIFOR practitioners (active): collaboration with scientists and *Airumakuchis* *Airumakuchis (active):* hunters/fishers who aim to secure livelihoods and sustainability	Social-ecological systems/ILK (Folke et al., 2016)	Santa Teresita Village in the Amazon Rainforest (Puerto Nariño/Leticia, Colombia)	Growing livelihood demands affect the consumption of wildlife for subsistence and trade as Indigenous knowledge and governance erodes	5 Workshops (10 people/ average), 15 interviews - 4 years

van Koppen and Spaargaren, 2015; Rosen. and Painter, 2019). In general science appears key to all co-production projects as science actors always have an "active" role.

Data was coded in two rounds and involved a reflection by the co-authors on which information and situations emerged, during their co-production process. Initial coding focused specifically on information related to questions 1 and 2 presented above, and with the three 'triggers' and 'guidelines' presented in Fig. 1. This coding supported the analysis of the emergence and mitigation of the challenges of knowledge differences and power imbalances, during co-production processes.

A second coding focused on the reasons why actors met challenges and/or successes to generate CLU knowledge and achieve sustainability. For example, when an interviewee stated that she did not adopt a change in resource management as planned during co-production, we checked whether this resulted from the 'rigid postures' of scientists and whether there were attempts at *deliberation* and *trust*. We analysed CLU based on our definition of these three concepts. We pay attention to manifestations of trust in co-produced knowledge (see Fig. 3), the extent of the inclusiveness in co-production, and the extent to which knowledge was deemed appropriate and feasible to be used. The effectiveness of sustainability implementation was not measured. As the cases focused on a qualitative analysis of co-production, we instead verified if transformative changes were in motion.

Finally, data from the cases were systematised per type of IPLC group, aiming to compare the specifics of co-production with different ILK systems. We then analysed the interplay between different challenges and guidelines with knowledge CLU and effectiveness and distilled principles and practices that led to co-production effectiveness.

4. Results

In this section, our analysis of the case studies is guided by focussing on the objective of this research, assessing the impacts of knowledge CLU on co-production effectiveness and the practices that help scientists to tackle knowledge differences and power imbalances. In all the cases, actors involved in co-production faced challenges related to knowledge differences and power imbalances. Furthermore, there was evidence in successful generation of knowledge CLU that these attributes yielded benefits for the adoption of changes in the management and governance of natural resources that have enhanced sustainability (Table 2). In table two we outline the challenges and successes of actors in achieving credible, legitimate, usable, and effective knowledge for each case, which we explain in more detail thereafter. We consider the challenges related to knowledge differences and power imbalances and the guidelines used to tackle them. These guidelines are used to structure the discussion following the results section.

In **Case 1**: Selective solid waste collection program in Minas Gerais, Brazil, scientists co-produced this program by working separately with citizens, as practitioners avoided engagement with them. Practitioners disregarded part of the scientific and local knowledge that citizens had assessed as credible and usable. Despite the efforts of scientists to sensibilize citizens to the program (e.g., citizen-to-citizen method; see Case 5), practitioners did not disclose and monitor the changes afterwards, making its adoption ineffective so far. In addition, the knowledge and values of citizens affected their inclination to adopt changes in their practice or not (Table 2).

Cases 2 and 3 are both 'science shop' projects, where universities fund and conduct sustainability research to address the demands of practitioners and citizens. In **Case 2**, New pocket parks in Amsterdam, The Netherlands, practitioners selected indicators to assess potential park locations, which scientists integrated into a GIS model at the city level. Scientists indicated which indicators the models could include, but practitioners had the final say in deciding on this. Practitioners validated these data on site and discussed future park management separately, with citizens. The effort to inform planning with knowledge that was usable to citizens was an important follow-up aimed at generating effective knowledge. In **Case 3**, Citizen management of a cultural stream in Driebergen, The Netherlands, scientists and practitioners co-produced an assessment with a small citizen group. They generated data that would help them update the management of a stream and its banks with Water Board practitioners. The project combined scientific knowledge with the knowledge developed by citizens who have managed and governed the stream for 25 years. Co-production resulted in knowledge that citizens found trustable and usable and that they are adopting in the revision of their management. However, the effectiveness of this adoption was not investigated and was recognised to be relatively fragile, as the practices of actors who were not involved in the process may influence falling water levels and poor stream water quality.

Fig. 2. Map with locations of the study areas where thirteen co-production case studies explored in the article were carried out.

Fig. 3. Co-production activities and/or their contexts. A: Case 1; B: Case 2; C: Case 3; D: Case 4; E: Case 5; F: Case 6; G: Case 7: H: Case 8; I: Case 9; J: Case10; K: 11; L: 12; M: 13.

In **Case 4**, Salt Mining impacts on settlements in Harlingen, The Netherlands, citizens contested the insufficiency of the Dutch system to measure mining impacts (see also Meesters et al., 2022). After extensive inter and transdisciplinary dialogue with scientists, citizens proved the inability of the system to establish causality between mining activities and future environmental damage. Through campaigns based on the idea of fair mining, the citizens persuaded the Ministry of Affairs and the mining company to adopt a (co-produced) monitoring system that can capture this causality and establish accountability (Table 2). Both citizens and the Ministry consider this system more credible, usable, and effective than the previously used. The monitoring system is now required and feeds into a national process to enhance environmental security. In contrast, in **Case 5**, Sustainable agriculture in Kockelscheuer, Luxembourg, a pilot project promotes the production and consumption of regionally grown food with citizens and farmers, to support the national 'resilience-zero carbon health transition' program (Keßler et al., 2022). Scientists and practitioners advocate that agriculture should be widely adopted in urban and rural areas. When dividing the agricultural area of Luxembourg by its population, we find 2000 m^2 of arable land per citizen that would be sufficient for them to cultivate food. The process was intended to be informative, but citizens and farmers pushed for co-production to create meaningful education and transition initiatives. Citizens considered the co-produced knowledge credible and usable for them, since it had meaning for their well-being and their environment. Most farmers recognised the ecological importance of the suggested changes but did not find them credible and usable for themselves, in view of the reduction of profit these changes could bring.

Additional cases focus on modern farmers, peasants and traditional communities, **Case 6**: Participatory agroecological research with peasants in São João Evangelista, Brazil stresses the need for creatively optimise project resources with rural communities to overcome geographical distances, see Cases 1, 7, 10 and 11 (Table 2). Also, as in these cases, scientists achieved a knowledge CLU in Case 6. This was verified as the social groups involved indicated to find the knowledge co-produced trustable, inclusive, and appropriate to enhance sustainability in their contexts. This success was met by the facilitators of co-production understanding local knowledge and needs first, and then deciding with IPLCs about scientific knowledge that was relevant for them, and by them reshaping project goals to align with these needs. The adoption of co-produced knowledge by peasants has taken place slowly. Although some of them argue that this is due to (youth) labour evasion and low income, others seem to increasingly regard their work as a hobby rather than as a full-time occupation. However, since the project lasted one year until now, more changes might still occur during its subsequent year of duration.

In **Case 7**, The community worked on co-producing sustainable practices in Siribinha, Brazil (see also Ludwig and El-Hani, 2020). Despite respectful dialogues and the treatment of local knowledge, scientists were not clear enough about research goals, (personal) motivations and in the benefits that fishers would have by participating in co-production. As fishers did not fully grasp the former, it limited their ability to co-create common goals or manifest their thinking about the process. Additionally, their focus on collecting objective data and local knowledge sometimes prevented them from including local concerns. This approach led many fishers to not see the value in participating in the project. Scientists did not know how to manage the situation and deal with the hierarchical relation that emerged, and the demotivation of fishers, limiting their participation in co-production. This constrained the generation of CLU. While CLU was achieved in co-produced practices, only few fishers of the community shared this view.

In **Case 8**, Making grape marc fertilizer in Schwebsange, Luxembourg, scientists and winegrowers co-produced a new fertilizer technology based on composting grape marc. Scientists established and maintained reciprocal engagement and trust with winegrowers by including local knowledge in the process of co-production and supporting winegrowers to adopt change - cf. Cases 2, 4, 6, 9–12.

Table 2
*Challenges and * *successes that actors met in each case to achieve credible, legitimate, usable, and effective knowledge, in view of challenges related to knowledge differences and power imbalances and of guidelines used to tackle them.

Challenges	Rigid theories/postures		Dominant methodological practices		Limiting time and money resources		Outcoming effectiveness
Guidelines **Case**	***Reciprocal engagement***	***Flexibility to reshape***	***Mutual understanding***	***Deliberation***	***Trust***	***Creativity***	***Sustainability changes***
Citizens and Local knowledge (LK)							
1) *Establish a selective (solid waste) collection programme*	* *Scientists interacted with citizens as equals but practitioners did not. *Practitioners avoided contact/ being confronted with citizen demands; and only partially accounted for the knowledge co-produced with them	*The lack of local social mobilization and political engagement required scientists to co-produce an assessment of problems/solutions with citizens and do planning with practitioners separately	* *Knowledge exchange and 'inheritance' between scientists and citizens were enabled by 1) the use of non-technical language; 2) by creating symmetrical relations and 3) through raising awareness and sensitization	*Practitioners disregarded key points which scientists asked them to consider (e.g. program monitoring and citizens' need of garbage containers in poor areas).	*Practitioners lack funds and time to divulge and monitor the program and as a result it doesn't get done and citizens lose trust in it	* *Scientists' creative solutions contributed to the acceptance of the program (e.g. educative traffic/ market interventions; games; electronics/oil collection points). *Practitioners did not divulge these creative aspects of the program sufficiently.	* *Citizens adopted the program (when they were aware of it or found it relevant) or * Waste management/ governance changed little because of deeply rooted values (faith in God's will), disbelieve in its relevance and lack of time.
2) *Searching for new pocket parks in Amsterdam*	* *Scientists and practitioners interacted as equals. *Practitioners engaged separately with scientists and citizens	* *Scientists and practitioners co-produced GIS indicators that could support the selection of locations to introduce small parks in urban areas of Amsterdam. *The complexity of modelling meant that programming was the exclusive work of scientists	* *Range and criteria for the indicators were discussed based on suggestions from the scientists; but the practitioners had the final say on the indicators used, based on their practical perceptions of the locations. *LK was only brought in through the practitioners during the modelling.	* *Scientists and practitioners shared power to co-produce indicators. *Citizens were not involved in the assessment. They *participated in the validation of the model while selecting the top locations and in planning their implementation	* *Trust was cultivated by practitioners with scientists (during the assessment) and citizens (during the planning)	* *Practitioners involved citizens in the assessment of locations. *When scientists could not visit locations due to COVID, practitioners decided to visit and select locations only with citizens and through online conferences.	* *Practitioners are creating/managing parks in the chosen locations with citizens *without the participation of scientists. *Scientists do not know how these parks are managed
3) *Updating the management of a cultural stream by citizens*	* *Representatives of all local actors actively involved in co-production	* *Research questions, goals, and methods (i.e., the content of questionnaires) were reshaped with citizens. Scientific measurements were linked to the knowledge of practitioners and the experience of the citizen in the history / practice of management.	* *All actors inherited knowledge from each other based on dialogue. A joint understanding to make decisions focused on the common goal of sustainable management. Citizens with a minority view (e.g., we should cut most trees) were not represented in decisions	*While evaluating management/ governance options, citizens sometimes wanted to lead decisions. Scientists negotiated with them, stressing their scientific independence	* *Trust was motivated by scientists and practitioners who valued citizen practices/ cultural heritage and listening to them	*The scientists did not participate in planning to update the management of the stream. *Citizens and practitioners took responsibility for this and made planning decisions based on the previous advice of the scientists.	* *The management plan is being revised by practitioners and citizens. *It remains uncertain how many citizens will actually adopt the planning and whether the water levels and quality will change.
4) *Avoiding harm from salt mining*	* *The citizens' status/lobbying campaign and the regional history of protests for better mining impacts measurements made the company engage/change	* *Via inter- and transdisciplinarity, citizens and scientists discredited and replaced the measurement system adopted in Dutch regulations to better account for mining impacts (soil	* *The co-produced 'Security Framework for the City' was based on a collective trust in scientific knowledge, a shared valuation of cultural heritage sites and	* *Citizens persuaded Ministry officials to allow the use of their framework arguing its validity/ usefulness as a pilot framework to guide mining licenses	* *Trust of the Ministry and the company was enabled by reciprocal trust among co-production actors, and since citizens wished for a fair procedure but did not pose a	* *Citizen creativity in lobbying and participation in the media enabled change (i.e., in proposing a pilot-frame/inter-/ transdisciplinary learning/ lobbying) for an adjusted mandate	* *Increased safety (e.g. mining stops if soil subsidence extends the prognosis). *Other citizen groups draw on the frame, and the procedure is presented as exemplary for other

(*continued on next page*)

Table 2 (*continued*)

Challenges	Rigid theories/postures		Dominant methodological practices		Limiting time and money resources		Outcoming effectiveness
		subsidence/ house damage/)	openness to dialogue.	*The audit committee did not engage due to its commitment to stay objective	significant threat/ opposition to mining	for the audit committee	cases in the Netherlands
5) 2000 m^2 *for sustainable agriculture*	* *Actors increasingly engaged to see meaning in changing their lives/being the precursors of the national transition	*Dialogues involved tensions (e.g., when actors felt criticized in their practices) *but these were managed and informed practice reshaping.	* *Growing awareness, problematizing / creating a solution at a demonstrative site; common goals on health/ sustainability united actors to evaluate/plan transition diets/ pathways	*Deliberation occurred, but is expected to evolve towards strongly implement/ monitor changes in the future	* *Trust was created/ maintained with efforts towards listening to others, inheriting knowledge, and respecting differences/ values before tensions	* *Actors co-created ideas to further the group and national transition, i.e., to engage young people, via social media; adopt community gardens; involve family/friends	* *Some citizens/ farmers are adopting organic horticulture and diets based regionally and seasonally and low in dairy/meat. *Conventional farmers see more profit in not changing to (certified) organic agriculture but are adopting agroecological techniques
Farmers and traditional communities, and LK							
6) Advancement of participatory research oriented to sustainability with agroecology	*Peasants' low education/political neglect required scientists to *stress research benefits to attract them. *Some peasants did not engage as the project involved policy practitioners who they do not trust	* *Scientists were flexible to translate technical terms into a simple language; address social/ economic/ environmental sustainability; and reframe methods before the temporalities of citizens/farmers	* *Scientists understood LK/ problems/needs with peasants to mobilize agroecological knowledge of peasants is valued as valid and relevant. Lab analysis added precision to deliberation	* *Knowledge exchange on problems/ current solutions followed by mutual deliberation/ practice demonstrations made co-production valid/relevant for peasants	* *A friendly relationship forged trust and participation.	* *Technical visits to peasants; spelling booklets and knowledge exchange in the market optimized co-production	* *Some peasants enhanced the productivity and diversity of their already sustainable practices, beginning to produce seedlings/ natural fertilizers and pesticides. *Project deadline and lack of peasant funds/labour limited changes
7) Knowledge and power in transdisciplinary research research	* *Scientists expressed respect for LK/routines and were introduced by a locally trusted scientist; *but did not explain research goals in a way fishers understood and became motivated	* *Scientists drew on local nomenclature and valued LK, but *dominated co-production in the process (not making agreements on methods/goals). Some locals felt motivated to participate but many others did not.	* *Scientists mirrored LK/ taxonomies with scientific correspondences, to communicate with locals; *but did not deliberate enough why	* *Often, agreement on how to change practices flew spontaneously. When it did not, *scientists avoided debate/ impose SK; to remain neutral	* *Scientists did not have the ability to discuss power imbalances openly. This broke the trust of many fishers in co-production, Interpersonal skills helped gain/regain trust of the community	*The Brazilian political context led to the reduction of funds and time for fieldwork creating focus on gathering data	*Only a fraction of the community stayed involved and motivated. *Those that remained are using the materials created and adapting practices (e.g., to conserve fishes/birds and cleaning beaches/ mangroves from rubbish)
8) CO_2*MPOSiTiv Grape marc - from underrated waste to premium fertilizer*	* *Winegrowers had the impetus to adopt the program/ project; established reciprocal engagement of practitioners/ scientists.	* *Knowledge inheritance and efforts from scientists/ practitioners to negotiate composting license with the government enabled co-production	* *Despite providing technical support, *it was hard to encourage the commitment of winegrowers to composting (it takes weeks, with repeated tasks every 2–3 days)	* *Non-hierarchical decisions enabled actors to create the (practical) knowledge that is being used by other actors	* *Practitioners stimulated trust by persisting in helping winegrowers install composting in their proximity and obtaining legal approval for it	* *Creativity was key to inventing a fertilizer using grape marc as a raw material	* *Winegrowers are producing fertilizer / increasing soil carbon storage. Composting is attracting winegrowers nationally. *Compliance with legal requirements remains a challenge
9) *Reducing turtle bycatch with small-scale fisheries*	*Scientists created engagement despite actors' different priorities (avoid turtle bycatch/	* *Flexibility to reshape postures, practices, and law was a common goal given the potential	* *Scientists worked alongside the fishermen to learn about their practices and also	* *Deliberation on management/ governance options included	* *Scientists enabled trust by moderating dialogue and making explicit	* *The solution adopted was to provide air spaces for turtles in the nets; however, its	* *Most fishers/ managers/ practitioners are using the co-produced

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Table 2 (*continued*)

Challenges	Rigid theories/postures		Dominant methodological practices		Limiting time and money resources		Outcoming effectiveness
	maintain fishing rates high) by working both together and independently	for gains if the research results led to regulation, practices that maintained livelihood/profits and were actually adopted	interacted with the fisheries managers to find a mutual understanding of the problem and possible solutions.	all knowledge holders and was ultimately based on solution feasibility / use in conjunction with regulations.	that the sustainability common goal could benefit all, if all cooperated and bridged knowledges	impact was not measured. *Bycatch still happens, but turtles are more likely to survive	knowledge. Compliance is enforced by regulations and more frequent net checks (e.g., in reproduction seasons)
Indigenous peoples and Indigenous knowledge (IK)							
10*) Legitimacy and effectiveness of co-production to mitigate climate change with Amazon Kaxinawás*	* *Practitioners established a fluid intercultural relationship with *Kaxinawás* by showing respect for/interest in understanding IK/ context/culture	*When translating IK mobilized with *Kaxinawás*, practitioners framed it to match scientific classification/ analysis; generating reports/maps that did not include IK as locals recognize it	* * Practitioners drew on IK classifications to weave soil classes with them and reflect on changes with them *Practitioners did not respond to the resistance of *Kaxinawás* to their form of translating IK;	* *Mutual reflection on changes/ common goals (biocultural diversity) and the feasibility of changes' feasibility (i.e., ecological state; local income) generated a planning the locals found valid/relevant	* *Reciprocal trust between practitioners and *Kaxinawás* optimized co-production, despite time/ money constraints (i.e., remoteness of the area)	* *Practitioners' creativity of practitioners (participating in local practices) optimized understanding of problems and solutions. Scientists managed *temporality differences by adjusting the methods and recalling their timeframe	* *Knowledge agents supported *Kaxinawás* to adopt practices/rules (i.e., agroforestry; agriculture focused on deforested areas). *Population growth/ neighbours' practices still pressure biodiversity/ climate
11) Reinforcing traditional food and medicinal practices with Amazon Kaxinawás	* *Scientists created a 'reciprocal' commitment by being friendly and respectful of IK); children also engaged / learned	*The vast experience of the ethnobotany team helped weave knowledge correspondences/ differences/goals and adapt to the temporality of IPs	* *Scientists departed from dialogue on local nomenclature indicators and weaved them with scientific taxonomies, via mutual understanding and knowledge inheritance.	* *All co-production processes and decisions were made with *Kaxinawás*. *Women engaged little in this case, as it was guided by male researchers. Man represented them	* *Co-production departed from creating trust with *Kaxinawás* (by being introduced by practitioners they trusted in; respecting local routines)	* *Practitioners optimized (split) the teamwork to assess/plan plants production/ consumption; created spelling booklets/and interactive games with the identified plants	*More changes could have been mediated if the area had not been so remote. * *Changes included new crops, revalorization of IK/identity/ practices that were viable in cropped/ forested areas
12) Conserving ecosystem services, agrobiodiversity, and health with Amazon Puyanawas	* *Practitioners created engagement by agreeing with leaders to use a different methodology than the one they planned *as they preferred to transfer the co-produced knowledge to other *Puyanawa*	* *Practitioners reshaped methods before local: political dynamics of leaders); focus on cassava trade; Indigenous temporality. Locals adapted IK/values/ goals to change before gain of awareness/learning in demonstration areas	* *Practitioners relied on interdisciplinary/ experiential knowledge (of previous co-production with IP) and *Puyanawas* *were already empowered (by previous projects), leading to dialogue based on IK	* *Deliberation was facilitated by *Puyanawas, who were* interested in sustainability / preservation of traditional practices (common goal); REDD + supports	* *Trust was developed by practitioners with respect to IK/governance and being introduced by practitioners, *Puyanawas* trusted	* *Actors raised cassava/ flour production, liberating labour to diverse agriculture; created community gardens; re-valorised/ rescued medicinal IK	* *Local knowledge agents and schools/ youth are supporting the adoption of changes and re-signifying agricultural practices. *Urban food consumption remains strong
13) Wildlife management with *Airumakuchis* in the Colombian Amazon	* *Engagement was obtained by scientists being introduced by people the locals trust and ensuring that IL/ expectations/ needs/practices are included throughout the process	* *Scientists reshaped the conceptual/ methodological premises to support the initiative of local leaders/ researchers to co-steer the process; and supported the setup of the 'Hunting Association of *Airumakuchis'*.	* *actors manage differences and created new knowledge/ capacities *Despite intracommunal conflicts (about the access to/ benefits from the project and the perception of appropriation of resources by associated members),	* * supporting the sustainable management and governance of wildlife secures an important regional food resource *Scientists dealt with the local trade of game meat (which contradicts conservation science/ Colombian laws)	* *Scientists frequent site visits (2–3 times/year) and transparent communication ultimately helped built trust with *Airumakuchis* *Despite efforts to build engagement, *Airumakuchis* distrusted scientists (thinking they wanted to exploit them/ their resources).	*Budget limitations stimulated new ideas - e.g., local leaders guide monthly workshops with other *Airumakuchi* members) and get compensation for this work. Updates have been sent through social networks (postings/videos).	*Documentation and valorisation of IK/practices that maintain access to wildlife resources are stimulating *Airumakuchis* to commit more to local rules and change management practices. The hunting association has strengthened the representativeness of hunters before public authorities

Winegrowers considered this knowledge credible, usable, and resultant of legitimate iterative processes. Winegrowers are also increasing the storage of soil organic carbon, and the generated knowledge inspires other winegrowers, evidencing co-production effectiveness. In **Case 9**, Reducing turtle bycatch in small-scale fisheries in Ontario, Canada, scientists, fishers, and fishery managers collaborated to minimise turtle bycatch (see also Larocque et al., 2020). They reached mutual understanding about bycatch while allowing fishers to continue their activities. Co-production efforts were felt as fair (legitimate) by the actors involved and led to a solution that was considered credible and usable by them, cf. Cases 3–6, 8, and 10–13. The adoption of this solution in practice was mediated through the enforcement of government regulations and conservation officers, as well as by the education of fishers and managers. Nevertheless, the effectiveness of this solution to enhance sustainability -in this case, by avoiding turtle bycatch- seemed to be questionable (Table 2).

In the cases involving Indigenous peoples, scientists and practitioners stressed the need to adapt to local processes of dialogue, deliberation, and decision-making (cf. Cases 6, 7). Respecting local norms and dynamics required scientists to put effort into establishing agreements with Indigenous leaderships. Distinct local temporalities were perceived to slow down scientific production and to be managed by interspersing different types of data collection (e.g., workshop activities and interviews) to optimise time (cf. Matuk et al., 2020a). While Indigenous peoples, scientists and practitioners could speak in a shared language, the latter learned and used the local language and classification the former employed to identify soils, fauna, and land management indicators to plan sustainability based on Indigenous knowledge cf. Cases 1, 6, 7.

Case 10 deals with the co-production of climate change mitigation in the Indigenous Land of *Kaxinawá* Nova Olinda, Brazil (see also Matuk et al., 2020b). Here, scientists and practitioners used IK-based oral communication and considered local needs. For this reason, *Kaxinawás* considered that the knowledge generated with them had CLU. They also adopted many changes (cf. Cases 11, 12). Almost all *Kaxinawás* quit cattle grazing (a non-Indigenous practice that damaged crops) to focus on game meat consumption. They also adopted rotative hunting practice to avoid increasing the pressure of hunting over the biodiversity of their fauna. Such changes have been considered effective in improving sustainability. However, practitioners also produced graphic materials (i.e., reports and maps) that represented Indigenous knowledge in ways that were unrecognisable and unusable to *Kaxinawás*. Although the former alleged that these materials were meant to be presented for other scientists, this lack of recognition indicates that these materials involved knowledge extraction (see also Matuk et al., 2020b). Additionally, *Kaxinawás* expressed that it would have been helpful for themselves to use these materials to transfer the co-produced knowledge to community members who did not participate in co-production. **Case 11** was also carried out with these *Kaxinawás*. Here, a different group of scientists planned how to support them in rescuing food and medicinal practices and improving sustainability (see Lanza et al., 2018). Although power issues did not emerge, this case was more aimed at documenting Indigenous knowledge and providing some support to locals in rescuing traditional practices. The challenge encountered was that although some *Kaxinawás* adopted changes to improve sustainability, the consumption of urban food and the internal migration of youth to study and work in the city limited the adoption of this direction.

Case 12 is about the preservation of ecosystem services, agrobiodiversity and health in the indigenous *Puyanawa* land, Brazil (see Amaral et al., 2021). In this case, practitioners and scientists applied a REDD^{+} policy while jointly searching with *Puyanawas* on how to enhance local sustainability and Indigenous health. Co-production respected *Puyanawa* norms of engagement. Leaders preferred to co-produce knowledge with the former alone and to transfer it to the rest of the community members later on. While this preference centralised the co-production decisions on leaders, to the detriment of the inclusion of other community members in these decisions, the co-production facilitators trained leaders as 'knowledge agents' to do this transfer in a way that could be adapted to the needs of different community members (cf. Cases 11–13). Although these arrangements were made, the challenge of adopting changes remained: *Puyanawas'* focus on cassava trade and is already widely used to consume processed foods imported into the community (cf. Case 10). This leaves little space for traditional polyculture and changing diets to minimize the consumption of urban food and the health issues that they have (e.g., obesity and diabetes). While the *Puyanawa* leaders considered the knowledge generated to have CLU, the exclusion of other community members from the process prevented them from being legitimately included. Ultimately, some members manifested to find meaning in the knowledge transferred to them, to improve their practices and the conservation of their livelihoods in their context. So, they consider this knowledge credible and usable. However, those *Puyanawas* who value more to focus on the cassava trade and the consumption of urban food do not see usability in this knowledge for themselves.

Finally, **Case 13**: Wildlife management with *Airumakuchis* in the Colombian Amazon covers challenges related to trade and consumption of game meat and the loss of traditional hunting practices in an Indigenous territory (see Hernández-Vélez et al., 2020; Krause and Tilker, 2022). Scientists dealt with this practice (usually considered unsustainable) by studying how it contributes to livelihoods and diets and supporting local approaches for sustainable management and governance. Scientists also found creative strategies to monitor fauna and harvest rates (Table 2). The inclusion of *Airumakuchis* in collecting and applying the obtained data generated knowledge CLU for them and led to effective outcomes.

5. Discussion and conclusions

The application of our conceptual framework to our 13 cases shows that challenges of knowledge differences and power imbalances arise during co-production processes in an intertwined manner. As we had argued, these challenges are indeed triggered to emerge when scientists and practitioners adopt rigid theories, postures and dominant practices during co-production (cf. Chambers et al., 2021; Matuk et al., 2020a; Turnhout et al., 2020). Moreover, when these triggers are present, they tend to reduce the ability of these actors to deal with the time and money limitations of co-production projects (c.f. Evans, 2006; Matuk et al., 2019, 2020a). Likewise, the guidelines 'reciprocal engagement and flexibility to reshape', 'mutual understanding and deliberation', and 'trust and creativity' enforce each other. Using one of them enables the other and helps co-production actors to work collaboratively to achieve knowledge CLU successfully.

Overall, knowledge CLU and co-production effectiveness are achieved in co-production processes by means of sharing of power between groups of scientists and practitioners and groups of IPLCs (cf. Matuk et al., 2020a), independently of the research field and methods used for participation. The cases show that sharing of power helps these actors reshape pregiven methods and frameworks to fit the co-production context e.g. type of the social group, the knowledge involved, the context specifics etc. By doing so, they get to better understand the knowledge and values of different actors and to align or deliberate on knowledge differences (cf. Lélé and Norgaard, 2005; Clark et al., 2011; Ingold, 2011; Tengö et al., 2017; Klenk, 2018). This helps them identify knowledge that is credible and usable in the situated context of co-production that goes beyond their previous conceptualizations of the said. Their understandings are then based on achieving ecological sustainability in practice, in each socioecological context (cf. Matuk, 2020).

Additionally, the challenges faced during co-production vary depending on the context of co-production itself, on the group of IPLCs, and on the ILK involved. This leads to differences regarding which knowledge content they find credible, legitimate, and usable (cf. Wheeler and Root-Bernstein, 2020; Matuk, 2020). It is important to distinguish that collaborating successfully with Indigenous peoples indispensably requires efforts to establish trust and develop agreements that respect local socio-political and temporal dynamics (Matuk, 2020), interdisciplinary and holistic thinking, and needs - Case 10–13 (cf. Lélé and Norgaard, 2005; Matuk et al., 2020b). Nonetheless, our data show that these agreements are also needed when co-producing with citizens, peasants, and traditional communities, especially in the Global South (Cases 1, 6, 7). In addition, co-production with actors from the Global North requires an emphasis on creating bonds of trust, agreements on goals and methods, and acquaintance with knowledge, worldviews, values, and needs of social groups. These agreements become more challenging as the actors involved in co-production often belong to different cultural backgrounds. They often hold different epistemologies, priorities, interests and goals. The key to transpose knowledge differences then, is to understand environmental problems in their social-ecological contexts. This requires navigating possible sustainable transformative changes with IPLCs, in ways that are feasible to be endorsed and executed in practice.

Below, we synthesise the insights we gained from our cases with a focus on the overarching objective of advancing the effectiveness of co-production in delivering sustainability transformative changes. Scientists, practitioners, and IPLCs working with co-production in other cases can use these insights as a set of effective principles and practices.

- ***To generate knowledge CLU, scientists and practitioners need to empower IPLCs, by enabling the creation of a reciprocal engagement and trust with them.***

When scientists and practitioners leave their 'rigid postures' and 'dominant practices' and share power with IPLCs in unbiased and friendly ways, this may contribute to higher chances of success (check Table 2). Generating an equal playing field for different knowledge systems contributes to inclusive ways of doing assessment and planning that promote sustainable outcomes (Díaz et al., 2015; Hill et al., 2020). The former can do so by being 'reflexive' to improve the process (cf. Klenk and Mehaan, 2017) and 'flexible' to shape forms of engagement, methods, and ideas (Chambers et al., 2022) – e.g., Cases 4–6 and 8–13. When they make space and give voice to IPLCs, they motivate participation. They, moreover, co-steer co-production by listening, reflecting together and giving credit to IPLCs. This guideline brings in reciprocity, optimises the time and money available, and triggers other elements of guidelines that tackle knowledge differences and power imbalances (cf. Matuk, 2020). By doing so, it generates knowledge CLU, which IPLCs are more likely to use in practice. Oppositely, when scientists and practitioners remain rigid, objective and exclude IPLCs from decisions, the "collaboration" stays conceptual and IPLCs might not engage (cf. Meehan et al., 2018) (Case 7). However, IPLCs do not remain passive to the former's approach - e.g., they may not be fully open to engaging themselves or using the knowledge generated in the process (Cases 1 and 5).

- ***CLU, and effectiveness are raised by involving IPLCs in the co-production of both environmental assessment and planning processes.***

  Assessments co-produced by one group tend to be insufficiently legitimate and usable for another group (cf. Nadasdy, 2003; Ayana et al., 2015). In Case 2, citizens did not participate in the co-producing assessment and planning. In Cases 2 and 3, scientists only participated in the assessment and not in the planning. However, the lack of scientists participating in the planning also prevented them from validating knowledge and witnessing co-production effectiveness. Despite these pitfalls, these cases importantly indicate an increasing use of co-production in Citizen Science and in other fields that address citizens (cf. Ottinger, 2009; Rosen. and Painter, 2019), to include citizens and their knowledge more fairly in the decisions that affect their lives.

- ***Scientists and practitioners need to use more graphical materials (e.g., maps, reports, and booklets) in addition to the oral communication they use with IPLCs to systematise and divulge co-produced knowledge for both scientific, policy, and social audiences.***

Case 10 illustrates that co-production can be mediated by oral communication of practitioners with Indigenous peoples based on the latter classification nomenclatures. This communication can result in knowledge that is considered legitimate and usable by Indigenous people. However, it can simultaneously involve the production of graphical reports and documents that show knowledge extraction. This extraction could have been prevented if practitioners would have responded to the resistance of *Kaxinawás* against their way of framing their knowledge to match scientific classifications (see also Matuk et al., 2000a). Doing so, would have allowed them to produce materials that were legitimate and usable also for *Kaxinawás* and not solely for themselves. In addition, we saw the use of graphic materials in co-production with Southern peasants, traditional communities, and Indigenous peoples (Cases 1, 7, 10 and 13). These materials help transmit knowledge exchanged and co-produced with IPLCs for community members who did not participate in co-production. Furthermore, some Indigenous peoples (Case 12 and 13) are seeking to rescue or support the wider adoption of traditional knowledge that is in the process of being abandoned by most locals. This knowledge can be registered graphically to help prevent this loss. In sum, graphic materials are a useful means of documenting knowledge and supporting changes.

- ***Actors sorting out knowledge differences need to deliberate on differences in an explicit manner, which requires facing divergences, focusing on common goals, and/or shifting values.***

As Haraway (2016, p. 1) states, actors must 'stay with the trouble' of differences in order to co-produce meaningful results. They do that, by reconciling differences - e.g., on conceptualisation of methods (Cases 4, 12) and solutions (Cases 5, 12–13) - or by making concessions that benefit the majority involved in (e.g., Cases 3, 4). In our cases, the actors 'mutually understood' and unravelled the reasons behind the differences that emerged. Usually, this took place during demonstrations of practices and while developing inter- and transdisciplinary collaborations. The actors generated new knowledge on management and governance strategies (Cases 8, 9, 12, 13) by 'inheriting knowledge' from each other (cf. Klenk, 2018). This resulted in shifting worldviews and values (e.g., Cases 4, 10) that crucially sensitised actors to deliberate on 'common goals' and fuelled their commitment to change practices (cf. Kenter, 2018; Matuk et al., 2020a).

- ***Strengthening the effectiveness of co-production requires involving more broadly in co-production actors from various spatial scales and sectors whose status quo of practices and institutions influence the ecosystems that IPLCs manage.*** Environmental conservation, climate change, and biodiversity loss involve actors at different scales whose practices may affect the areas addressed with co-production. However, co-production usually includes actors located in local or regional areas – e.g., Cases 4, 5, 7, 8–10 and 12. The participation of external actors in these areas could enhance the change in areas addressed with co-production, incentivizing these actors to also adopt changes that prevent them from affecting IPLCs' ecosystems (cf. Matuk, 2020; Chambers et al., 2022). Additionally, the participation of external actors could lead them to adopt changes in their practices that would support IPLCs to improve the sustainability of their practices (Case 5). Especially in Case 4, actors engaged in co-production in a way that generated changes in both social, policy, and entrepreneurial practices. Cases 5 and 9, in turn, demonstrate that changes can be limited when the goal of maintaining profits or existing practices is expected to lead to enhancing sustainability. This is made clear through examples of conventional farmers who preferred to stick to organic agriculture and fishers who remained using nets that cause bycatch. Furthermore, despite the fact that Indigenous people generally focus on subsistence, some of these peoples focus on trade, restricting the adoption of sustainability changes (Case 12, 13). These cases call for transformations in the *status quo* of science, policy, and social practices to support IPLCs enhancing sustainability. They also call for technologies that ground economic profit in sustainability (cf. Chambers et al., 2021). However, these transformations must carefully consider the dangers of commodifying the resources and knowledge involved (cf. Buscher and Fletcher, 2020).

- ***While generating knowledge legitimacy and usability leads to greater credibility and effectiveness, ensuring effectiveness requires co-production projects to extend their time, resources, and goals towards consolidating changes.***

Scientists and practitioners generated legitimate knowledge when they provide opportunities for IPLCs to take part in co-production decisions. As these decisions bridge elements of scientific knowledge and ILK that are relevant for needs and contexts of IPLCs, the legitimacy of this knowledge is interdependent with its usability (Cases 4 and 6–13). Legitimacy is also required to address knowledge credibility and usability and therefore a key quality of co-production. Moreover, legitimacy works intertwined with effectiveness e.g., together, ILK and scientific knowledge enhance sustainability in its social, economic, and ecological dimensions (Cases 2, 3, 5, 7, 8, 10–13) (cf. Folke et al., 2016). However, the changes adopted indicate the potential rather than ensuring sustainability. We saw our cases neither analyse the long-term effects of changes nor measure the enhancement of sustainability.

In conclusion, challenges related to knowledge differences and power imbalances vary by group and context. Nonetheless, knowledge CLU and effectiveness are promoted simultaneously, mainly when co-production empowers society via fair and respectful processes. These processes should treat IPLCs and ILK in a non-hierarchical mannerand generate knowledge that is legitimate to both scientists, practitioners and society. To do so, the holders of scientific knowledge and ILK unravel their epistemological and ontological differences by reciprocally reshaping the methods, knowledge, worldviews and practices involved in co-production. An attentive, proactive, enlightening, and friendly attitude towards IPLCs greatly supports this. In general, knowledge that different actors find credible and usable is often considered legitimate and effective. Knowledge that is credible, usable, and effective can be the result of a process that does not directly include all IPLCs' community members and that is partially legitimate. Therefore, effectiveness is relatively independent of legitimacy (cf. Cash et al., 2003) if it succeeds in generating knowledge that is credible and usable to address the specific needs and context of the actors who will use this knowledge to improve sustainability in their contexts. Legitimacy, however, is the key quality of co-production and the means, we conclude, to address knowledge credibility and usability. Rather than focusing on scientific criteria to validate knowledge CLU, actors should focus on criteria that are situated in the context of co-production and address common goals that link sustainability and livelihoods.

Two shifts are urgently needed to advance co-production effectiveness. First, elevating society before science-policy interfaces to create legitimate co-production processes. This equal treatment of different knowledge systems will generate credible, usable, and effective knowledge. Efforts to be flexible and accept IPLCs' ways of validating knowledge CLU and effectiveness are of the essence. Second, scientists need to shift the focus from co-production conceptualization to its practice, and from idealizing ways of categorizing knowledge that bears CLU to identifying knowledge that is feasible to be adopted and to enhance ecological sustainability in each context of management and governance practices. A better understanding of the effect of the changes adopted by IPLCs on ecological sustainability is lacking. There is also a lack of broader inclusion of actors whose practices affect these changes. This shows that a sustainable future on Earth calls for social-science-policy interfaces, with a deeper collaboration among social scientists (who study co-production practices), natural scientists (who study ecological sustainability) and IPLCs (who traditionally transform resource management and governanace).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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