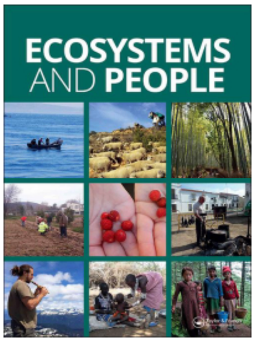

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RESEARCH PAPER

People working with nature: a theoretical perspective on the co-production of Nature's Contributions to People

Bruno Locatelli [a], Elena M. Bennett[b], Matthew J. Colloff[c], María R. Felipe-Lucia[d], Russell Gorddard[e], Ignacio Palomo[f] and Sandra Lavorel[g]

[a]Forests and Societies, CIRAD, University of Montpellier, Montpellier, France; [b]Department of Natural Resource Sciences and Bieler School of Environment, McGill University, Montreal, Quebec, Canada; [c]Fenner School of Environment and Society, Australian National University, Canberra, Australia; [d]Instituto Pirenaico de Ecología, CSIC, Jaca, Spain; [e]Land and Water, CSIRO, Canberra, Australia; [f]IRD, CNRS, Grenoble INP, IGE, Université Grenoble-Alpes, Grenoble, France; [g]Laboratoire d'Ecologie Alpine, CNRS, Université Grenoble Alpes, Université Savoie Mont-Blanc, Grenoble, France

ABSTRACT

The co-production of Nature's Contributions to People (NCP) is a set of processes in which anthropogenic inputs (i.e. material or non-material actions and the assets supporting these actions) and natural inputs (i.e. ecological structures and processes) interact to produce NCP. An interdisciplinary understanding of NCP co-production can support decision-making on ecosystem management or NCP use, given natural constraints, limited human inputs, possible adverse effects and trade-offs arising from co-production. In this paper, we show that mechanisms of co-production at the ecosystem level and the NCP flow level are fundamentally different. At the level of ecosystems, people manage natural structures and processes to influence the production of potential NCP (e.g. via planting, restoring, fertilizing). At this level, anthropogenic inputs can partially substitute for natural inputs, but natural inputs are necessary whereas anthropogenic inputs are not. At the level of flows, co-production actions convert potential NCP into realized NCP and quality of life (e.g. via harvesting, transporting, transforming, consuming, and appreciating NCP). At this level, anthropogenic inputs are complementary to natural inputs, although some substitutability can occur at the margin. Analysing the substitutability and complementarity between natural and anthropogenic capitals, as well as the adverse effects or mutual enhancement between them, is crucial for informed decision-making on landscape and NCP management. This understanding enables the identification of strategies that can ensure NCP supply and increase human well-being in a sustainable manner.

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1. Introduction

Most Nature's Contributions to People (NCP) and Ecosystem Services (ES) are not produced by nature alone but rather result from interactions between people and nature. The production of ES generally requires not only ecosystems but also some form of human intervention (Palomo et al. 2016). This essential fact is increasingly referred to as ES or NCP co-production (Spangenberg, Görg, et al. 2014; Fischer and Eastwood 2016; Palomo et al. 2016). Co-production does not necessarily mean that co-produced NCP would not exist without human intervention, but that they would be different in quantity and quality. For example, the regulation of the water cycle exists naturally but can be enhanced by people through vegetation or soil restoration and its contributions to human well-being can be increased by improving water distribution (Grantham et al. 2022). The co-production of NCP has been recognized by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in its conceptual framework on the interactions between the natural world and human societies (Díaz et al. 2015; Bruley, Locatelli, and Lavorel 2021).

How NCP are co-produced by social – ecological systems is a crucial question for managing natural resources sustainably and improving human well-being (Bennett et al. 2015; Rieb et al. 2017). For example, to enhance the landscape contemplation experience of visitors in a park, co-production actions may focus on improving scenic beauty (e.g. by planting trees with diverse shapes or colours or removing unpleasant landscape elements) or facilitating access and enjoyment (e.g. by improving trails, removing view-blocking infrastructure, or informing people about the aesthetic experience). These two forms of co-production may have different outcomes for the NCP of aesthetic experience and visitors' wellbeing, thus justifying the identification of the most effective

CONTACT Bruno Locatelli bruno.locatelli@cirad.fr
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actions. They can also have different effects on ecosystems and other NCP. For example, planting trees may affect biodiversity or water availability, whereas improving trails may lead to overcrowding and ecosystem degradation. These two forms of co-production may also have different distributions of costs and benefits among stakeholders, which can raise equity concerns (Palomo et al. 2016).

Transitions to sustainability require an understanding of the role of human actions in NCP co-production (Kachler et al. 2023). Analysing the interrelationships between natural and anthropogenic inputs, particularly whether anthropogenic inputs complement or substitute for natural capital, can help identify actions for restoring natural capital or using it efficiently and sustainably (Rieb et al. 2023). These actions can contribute to sustainable landscape management strategies and adaptation to changes in ecosystems and NCP due to climate change (Bruley, Locatelli, Colloff, et al. 2021). Identifying the drivers and effects of co-production actions can support policy decisions for removing barriers or activating levers, while avoiding adverse effects and reducing trade-offs (Torralba et al. 2018). Co-production analysis can also broaden the range of options for managing ecosystems sustainably and improving human well-being (Palomo et al. 2016).

Despite an increasing recognition that NCP are co-produced by people and nature (Mastrángelo et al. 2019; Kachler et al. 2023) and recent academic advances on NCP co-production (reviewed in the next sections), several challenges remain. Among them, an important gap relates to the descriptive nature of many co-production studies, which overlook the 'processes' or 'mechanisms' through which anthropogenic and natural inputs interact (e.g. complement or substitute for each other) (Isaac et al. 2023). This gap limits the opportunities to develop testable hypotheses and theories regarding NCP co-production and to support decision-making (Kachler et al. 2023).

In this paper, we first explore the definitions and origins of the NCP co-production concept in the literature (Sections 2 and 3). Despite the conceptual differences between NCP and ES (Kadykalo et al. 2019), we sometimes use the terms interchangeably. We mainly use NCP terminology but refer to ES when we build on previous research on ES. Our literature review is based on a search in Scopus on 6 October 2022 for papers that include ES or NCP in their titles and co-production (or similar terms such as 'co-producing') in their titles, abstracts or keywords (see search details and list of 50 papers in Supplementary Material S4). The literature review confirms the need to explore co-production mechanisms, which is done with a simple framework (presented in Section 4 and illustrated in Section 5). We present several building blocks of a theory development that defines important concepts, elaborates relationships between them, explains their underlying logic, and explores their operational linkages (Whetten 1989; Wacker 1998; Shoemaker et al. 2003). The substitutability and complementarity between natural and anthropogenic inputs in co-production are analysed in Section 6, before empirical data is used to illustrate our approach (Section 7). Our work contributes to building an interdisciplinary understanding of NCP co-production, towards a theory of its mechanisms with formalized assumptions, hypotheses, and some empirical evidence (Soga and Gaston 2022).

2. Definitions of co-production

NCP co-production is defined in three ways in the literature: as an interaction process, as inputs to this process, or as human actions (see list of definitions in Supplementary Material S1). First, co-production can be presented as a process or a mechanism of interactions between people and ecosystems that lead to the provision of NCP (Fischer and Eastwood 2016). An example is the 'joint production of ES by social and ecological processes' (Palomo et al. 2016). The idea here is different from joint production in ecological economics (i.e. the production of joint outputs, such as pollution together with desirable goods) (Baumgärtner et al. 2001), whereas NCP co-production focuses on joint inputs. Second, co-production can be described as inputs to a process, i.e. the natural and anthropogenic capitals that result in NCP (Jones et al. 2016). Anthropogenic capitals can be human skills, knowledge, workforce, social cohesion, produced goods such as machinery and tools, or financial resources (Goodwin 2003). Third, co-production can be human actions, either material or non-material, that people do to co-produce NCP (Bruley, Locatelli, and Lavorel 2021), for example, managing ecosystems or visiting a site (Torralba et al. 2018).

The literature on cultural ES clearly focuses on the role of ES beneficiaries as co-producers through the attribution and the construction of meaning to ES (Fischer and Eastwood 2016): people enjoying a walk in the woods 'create' the recreation ES, thus they co-produce it. Other definitions differentiate human actions at different steps of the ES cascade, from ecosystem management to service mobilization and appreciation (Fedele et al. 2017) (see comparison of conceptual frameworks in S2).

Building on these three types of definitions, we propose a short definition of co-production as people working with nature to produce NCP. We define NCP co-production in more detail as a set of processes in which anthropogenic inputs (i.e. material or non-material actions and the assets supporting these actions) and natural inputs (i.e. ecological structures and processes) interact to produce NCP.

To avoid misinterpretation, it is important to remember that the term 'co-production' is often used differently to describe interactions among people; for example, knowledge co-production by scholars and citizens (Wyborn et al. 2019; Norström et al. 2020) or co-production of goods and services by individuals from different organizations (Ostrom 1996), which is not what we mean here.

There may be some ambiguity regarding what qualifies as co-production, as shown by two examples. The first one is about pumping water from a river (natural inputs: water provided, regulated, and partly purified by ecosystems) and treating it (anthropogenic inputs: technological treatment) to produce drinkable water. The second example is about developing urban parks (natural inputs) and indoor air-conditioning (anthropogenic inputs) to reduce the impacts of heatwaves on urban inhabitants. On the one hand, these examples may not qualify as co-production because natural functions (i.e. water purification, cooling) are replaced by technology, which means that anthropogenic inputs decrease the need for natural inputs. For example, efficient air-conditioning decreases the need for urban parks and their cooling effect, as this natural cooling is replaced by a machine. On the other hand, one can argue that the first example is about co-production because natural and anthropogenic inputs are combined to support wellbeing from drinkable water and the technology helps benefit more from natural inputs, i.e. water from a river. The second example is less about co-production and more about replacement, given that air-conditioning does not help benefit more from natural inputs, i.e. a cool outdoor temperature.

3. Origins of the co-production concept

A review and classification of papers on NCP co-production and a citation analysis (Supplementary Material S4) highlighted four origins of the co-production concept (Figure 1, top box). First, research on cultural ES has shown how ES are culturally produced and cannot exist without human non-material actions that give meaning to them, such as sensing, feeling or thinking (Chan et al. 2012; Raymond et al. 2018; Pramova et al. 2022). Second, social-ecological systems approaches have identified the factors that influence ES and their contribution to human well-being and have highlighted the joint contributions of anthropogenic and natural inputs in ES (Reyers et al. 2013; Huntsinger and Oviedo 2014). Third, several papers have built on the ES cascade framework (Haines-Young and Potschin 2010), which represents a flow of ES from ecosystems to people, and added human actions to recognize that ES are more than 'nature's free gift to humankind' (Spangenberg, Görg, et al. 2014, p. 41; Spangenberg, von Haaren, et al. 2014; Fischer and Eastwood 2016; Jones et al. 2016; Fedele et al. 2017). Fourth, the IPBES framework (Díaz et al. 2015) clearly framed the provision of nature's benefit to people as

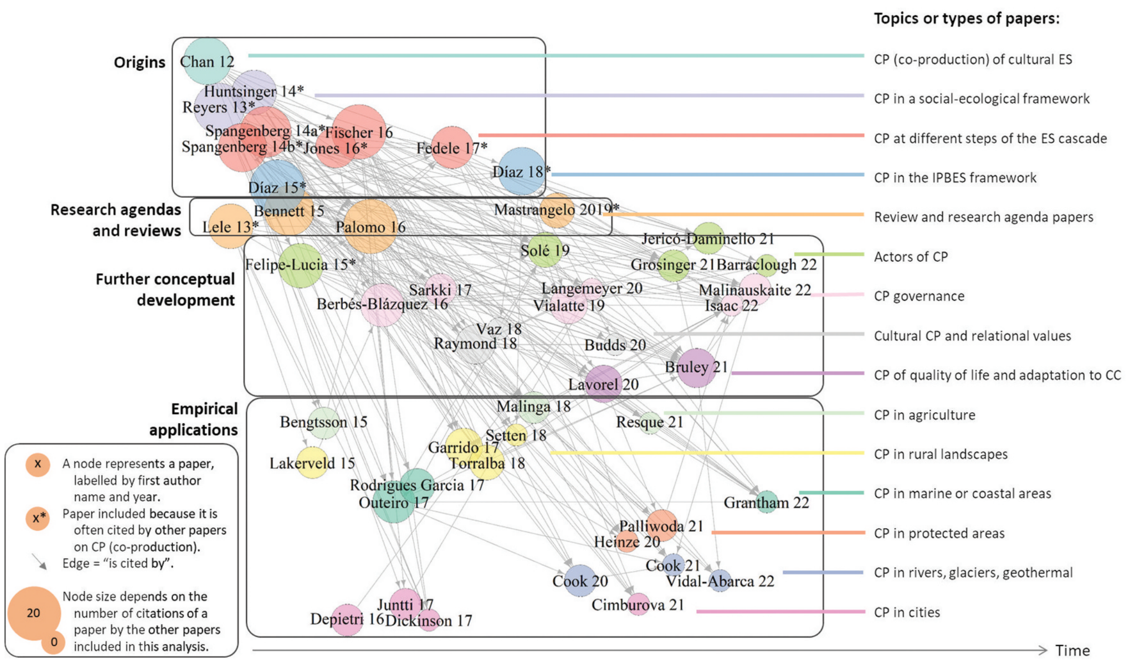

Figure 1. Directed graph of citations among papers on NCP co-production. Publications are represented by circles linked by arrows for citations (see detailed results in S3 and full references in S4). Publications are organized thematically (vertical axis) and chronologically (horizontal axis). Colours differentiate among topics or types of co-production papers. Boxes delimit the main four bodies of co-production research identified.

dependent on the ‘contribution of nature and anthropogenic assets, in a process sometimes referred to as “co-production”’ (p. 6), citing two papers on social-ecological systems approaches (Reyers et al. 2013) and human agency along the ES cascade (Spangenberg, Görg, et al. 2014). Other epistemic communities have put forward concepts akin to co-production; for example, metabolic approaches and territorial ecology represent landscapes and flows of matter and energy as a metabolic labour between humans and nature (Parascandolo and Tanca 2015; Buclet 2021). Most co-production literature appears to focus on Non-Indigenous settings, although many Indigenous Knowledges point out the importance of reciprocal gift-giving between people and nature, which is a kind of co-production (Kuokkanen 2006).

Conceptual developments on NCP co-production have benefited from several key reviews or research agenda papers (Lele et al. 2013; Bennett et al. 2015; Palomo et al. 2016; Mastrángelo et al. 2019), which have been widely cited subsequently (see arrows in Figure 1). Most further conceptual developments have concentrated on two topics (Figure 1, third box from top): (1) co-production actors, their perceptions (Jericó-Daminello et al. 2021), networks (Barraclough et al. 2022), collective capabilities (Grosinger et al. 2021), and power relations (Felipe-Lucia et al. 2015; Solé and Ariza 2019); (2) co-production governance (Isaac et al. 2022), including landscape governance for co-production (Vialatte et al. 2019), access and co-production (Berbés-Blázquez et al. 2016), the cascade of governance services (Sarkki 2017), governance and governability (Malinauskaite et al. 2021), and justice in co-production (Langemeyer and Connolly 2020). Other conceptual developments have focused on more specific aspects, e.g. co-production of quality of life (Bruley, Locatelli, and Lavorel 2021), co-production of adaptation to climate change (Lavorel et al. 2020), and cultural dimensions of co-production (Raymond et al. 2018; Vaz et al. 2018; Budds and Zwarteveen 2020). The co-production concept has been used for diverse empirical applications (Figure 1, bottom box).

4. A novel co-production framework for sustainability

Our literature review has shown the need to explore co-production mechanisms. For this, we propose a simple framework that differentiates two types of co-production: at the flow level (CPF) and at the ecosystem level (CPE). At both levels, co-production involves human actions that are influenced by drivers (Figure 2).

This co-production framework is inspired by the ES cascade (Haines-Young and Potschin 2010; Spangenberg, von Haaren, et al. 2014; Fedele et al. 2017) and IPBES framework (Díaz et al. 2015; Bruley, Locatelli, and Lavorel 2021). The framework considers the supply of potential NCP by ecosystems and the contributions of realized NCP to the quality of life of people who benefit from NCP (Figure 2). Potential NCP result from ecosystem structures and functions, but are not yet received or used by people (e.g. edible plants in a forest, colours in a scenic landscape), whereas realized NCP are the flow of NCP that reaches beneficiaries and contributes to their quality of life (e.g. nutrition, aesthetic pleasure) (IPBES 2019). The distinction between potential and realized NCP/ES is common in the literature, although various terms are used (Burkhard et al. 2014; Spangenberg, von Haaren, et al. 2014; Potschin-Young et al. 2017). This distinction is useful here to differentiate co-production influencing either potential or realized NCP.

The proposed co-production framework considers key actions, drivers, actors and feedbacks. Co-production actions occur at two levels in our framework: ecosystem and flow. The capacity of ecosystems to supply NCP results from natural processes and human co-production actions at the ecosystem level (CPE in Figure 2). At this level, examples of actions include conserving a forest, restoring a wetland, converting a forest into cropland, fertilizing soils, and planting or pruning trees. Realized NCP and their contributions to a good quality of life depend on potential NCP supplied by ecosystems and human co-production actions at the flow level (CPF in Figure 2). Example of actions include harvesting fruits, transporting water, traveling to visit a national park, transforming crops into food, enjoying a scenic view, consuming fruits, and appreciating the existence of iconic species.

Co-production actions are not always needed or possible. In the example of global climate (Figure 2), ecosystems can remove carbon from the atmosphere without any human interventions (CPE), although management is sometimes applied to improve carbon removal (e.g. carbon forestry). In turn, at the level of NCP flow, no human actions can influence how carbon removal results in climate regulation and contributes to reduced risks from global climate change.

8Co-production actions are influenced by many drivers, including broad values (ethical precepts that refer to desirable motivational goals and serve as standards for how people select actions and evaluate events) (Gorddard et al. 2016), values attributed by people to nature (Pascual et al. 2023), and the availability of capitals (tangible and intangible anthropogenic assets that people use for co-production actions) (Palomo et al. 2016). Rules are also important drivers, including rules-in-form (regulations, laws, etc.) or rules-in-use (social norms and practices, taboos, etc.) that define people’s rights to access or use NCP, determine how decisions are made on NCP (Colloff et al. 2020) or, more generally, influence people’s

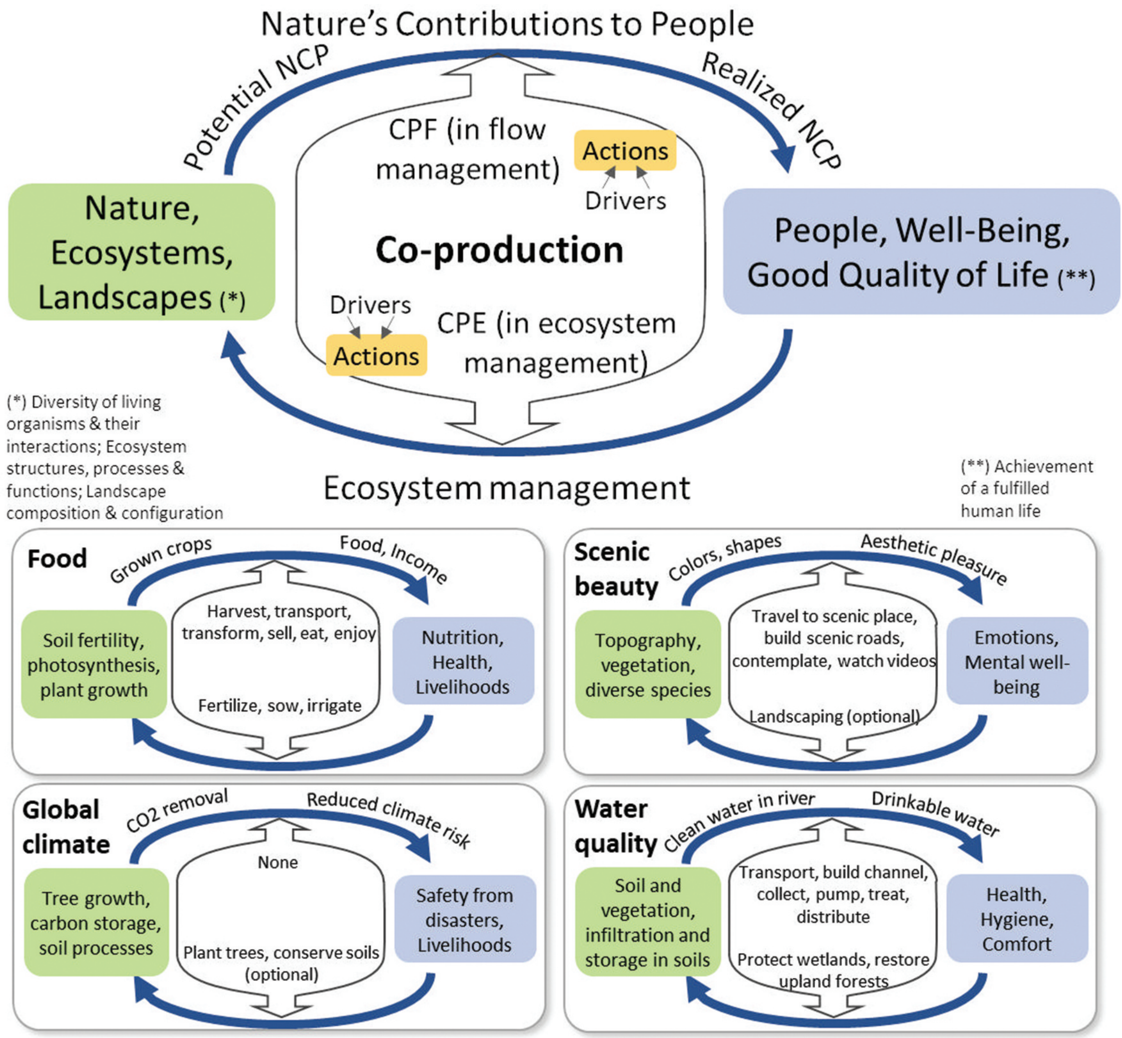

Figure 2. Framework of NCP co-production at ecosystem level (CPE) and flow level (CPF) and four examples.

behaviours (Colloff et al. 2017). Other driver typologies identified in the literature are identities and capabilities (Fischer and Eastwood 2016; Grosinger et al. 2021), human, social, manufactured, and financial capitals (Bruley, Locatelli, and Lavorel 2021), or rules, assets, values, and space (Fedele et al. 2017).

Co-production actors are diverse. Indeed, different people contribute to co-production close to ecosystems, along the flows of NCP, or remotely (Vialatte et al. 2019). For example, for scenic beauty, co-production actors include tourists, residents, photographers, park managers, and tourism professionals. Food co-production involves farmers in CPE, and wild food gatherers, transformers, traders, and consumers in CPF. A co-production perspective is useful to explore the different roles and the power relationships among co-production actors, which determine access to NCP and influence the choice of anthropogenic capitals used in co-production (Felipe-Lucia et al. 2015; Vallet et al. 2019).

Co-production is subject to multiple feedbacks and effects on other NCP, which lead to trade-offs and synergies between NCP. First, the co-production of an NCP at the flow level can incentivize the co-production of the same NCP at the ecosystem level, as the appreciation of an NCP can lead to the protection or restoration of ecosystems providing this NCP (Lavorel et al. 2020). For example, the recognition of the role of forests in climate regulation has led to conservation initiatives and new rules, such as payments for carbon sequestration and the REDD+ mechanism (Reducing Emissions from Deforestation and forest Degradation). Second, the co-production of an NCP can have adverse effects on the co-production of the same NCP. In the example of scenic beauty, too many tourists visiting a place (as CPF) may degrade ecosystems through trampling or littering (negative effect on CPE) or may reduce appreciation through congestion (negative effect on CPF) (Schirpke et al. 2020). Third, the co-production of one NCP can adversely affect the co-production of other NCP. For example, planting trees for carbon sequestration and global climate regulation (as CPE) can affect food production through competition for land and water resources (Locatelli et al. 2015).

Co-production can be unsustainable. In interventions such as monoculture tree plantations aimed at rapid wood production, as well as in various other cases, human interventions lead to the co-production of ecosystems markedly different from their natural state, often exhibiting low biodiversity and resilience (Locatelli et al. 2015). Moreover, such interventions typically prioritize the supply of a specific NCP, such as wood, at the expense of other important NCP for sustainability, such as water supply (Bonnesoeur et al. 2019). They may also generate social injustices when the favoured NCP predominantly benefit one stakeholder, while the repercussions of degraded NCP disproportionately affect other stakeholders (Vallet et al. 2019). While there is no normative stance in the definition of co-production, it is imperative to adopt a critical perspective when analysing co-production to inform the development of sustainable strategies (see discussion).

5. Diversity of interactions in co-production

We posit that the roles of human co-production actions and co-production mechanisms are fundamentally different at the ecosystem level (CPE) and the flow level (CPF), therefore with different implications for management and sustainability. CPE is about influencing natural structures and processes to enhance potential NCP, whereas CPF is about converting potential NCP into realized NCP and quality of life.

5.1. Interactions in co-production at the ecosystem level (CPE)

At the ecosystem level, there is a continuum of co-production actions from less to more anthropogenic inputs (Table 1): (1) let nature work to produce potential NCP (e.g. conserving a forest); (2) restore, enhance, or replace natural assets for increasing potential NCP (e.g. improving soil fertility with fertilizers, planting plants with a specific purpose), and (3) actively maximize a specific natural function for the production of an NCP (e.g. managing domesticated crops and animals).

At the ecosystem level, natural inputs are always necessary, even though they may be limited in the case of technological agricultural systems (e.g. hydroponic production). However, human actions are generally optional for the production of potential NCP. For example, without any human intervention, a forest regulates water, stores carbon, produces wood, hosts mushrooms and game, or provides potential recreation areas, but human interventions can enhance the delivery of potential NCP, for example by planting adequate species for wood production or modifying the ecosystem structure to improve recreation areas.

In some agricultural systems, human actions may seem necessary or, at least, very high because we have created systems that cannot function without us. For example, modern domestic cows are designed to maximize meat and milk production and require human interventions to feed and care for them. Similarly, many plants that have been artificially cultivated for centuries could not grow without people planting and managing them. These examples are extreme cases of crop and animal production along a gradient, from unnecessary anthropogenic inputs (e.g. wild foods) to anthropogenic inputs as enhancers (e.g. extensive agriculture), essential inputs (e.g. intensive agriculture with fertilization and irrigation), to absolutely necessary (e.g. intensive agriculture with highly domesticated animals and crops).

Table 1. Examples of co-production at the ecosystem level.

Amount of anthropogenic inputs	Natural inputs	Human actions	Outputs: Potential NCP	NCP type
No or limited: No human actions or protection actions to let nature work to produce potential NCP	Habitats, species, plant growth	No actions or protection	Iconic species, Scenic beauty, Wild food, Clear water	Non-material and material
Medium: Human actions restore, enhance or replace natural assets for increasing potential NCP	Insect diversity in hedgerow	Restoring and managing hedgerow	Pollination, pest control	Regulating
	Soil fertility	Fertilizing soils in agriculture	Crop production	Material
	Shapes and colors of trees	Planting ornamental trees in an urban park	Scenic landscape	Non-material
	Capacity of soils and aquifer to store water	Building infiltration trenches	Water regulation	Regulating
High: Human actions actively maximize a specific natural function for the production of an NCP	Animal physiological process	Managing cattle (including feeding, milking, treating diseases)	Intensive cattle production	Material
	Fish biological development	Applying aquaculture techniques in a fish pond or at sea	Aquaculture fish	Material
	Natural plant growth, Soil and its fertility	Planting domesticated crops, including preparing soil, planting or sowing, fertilizing, weeding	Crops	Material
	Capacity of some plants to extract pollutants from soils	Selecting and planting the best plants for this purpose	Cleaned lands	Regulating

5.2. Interactions in co-production at the flow level (CPF)

At the flow level, co-production includes a diversity of actions that materially or non-materially convert potential NCP into realized NCP and quality of life (e.g. mowing fodder for cows, milking cows, transforming milk into cheese, exchanging cheese for money, eating the cheese for nutrition, enjoying its taste, appreciating the quality of grassland that gives flavour to the cheese).

Co-production actions depend on NCP attributes relative to space (Table 2). If NCP are transportable (e.g. material NCP such as crops or water), a frequent co-production action is transporting them (e.g. bringing crops to a market, building a canal to transport water). If NCP are localized and not transportable (e.g. scenic beauty, flood mitigation, local climate regulation, pollination), co-production actions can move beneficiaries close to them (e.g. travelling to visit a scenic place, building a house close to an urban park to benefit from scenic views and natural cooling during heatwaves, or planting crops close to a forest to benefit from pollination). Some non-transportable NCP can contribute remotely to quality of life through specific immaterial transport (e.g. broadcasting the beauty of a place through videos).

Co-production mechanisms and the role of anthropogenic inputs at the flow level depend on whether NCP are subject to rivalry or congestion, two common concepts in economics (Adams and McCormick 1987; Birulin 2006). An NCP is rival (or subtractable) if its consumption by one person necessarily diminishes its use by others. Because of rivalry, there are physical limitations in the conversion of potential NCP into realized NCP (e.g. it is not possible to increase indefinitely the mass of food produced from a given mass of crops) and to quality of life (e.g. if I eat food, it is no longer available to other people) (Table 2). A non-rival NCP is prone to congestion if it could turn into rival after a certain level of use, i.e. if there are too many users, additional

Table 2. Examples of co-production at the flow level.

NCP attribute	Potential NCP	Human actions	Outputs: Realized NCP and quality of life	NCP type
Transportable NCP: human actions can include transporting the NCP	Crops, Wild food	Harvesting, transforming, transporting, selling	Food availability, nutrition, health, income	Material
	Water	Transporting water with tankers. Building irrigation canals	Water availability, nutrition, health	Material
Localized and non-transportable NCP: human actions can locate beneficiaries in places where NCP flow	Regulation local temperatures	Deciding to live close to a urban park to benefit from natural cooling during heatwaves.	Health	Regulating
	Pollination, pest regulation	Locating crops close to a forest to benefit from pollination	Food production (and ultimately nutrition, health, income)	Regulating
	Scenic beauty, Recreation	Travelling to visit a place or practice outdoor activities	Satisfaction, inspiration, mental well-being	Non-material
Non-localized NCP: human actions cannot direct flows (but can still influence outputs)	Global climate regulation	No human actions needed to direct flows. Outputs depend on people's vulnerability (as a function of their capitals for example)	Security, health	Regulating
	Iconic or symbolic species	No human actions needed to direct flows. Outputs depend on human assets or actions (e.g. knowledge, education)	Identity, sense of place	Non-material
Rival NCP: The amount of potential NCP limits outputs, whatever the level of human action	Crops, Wild food	Harvesting crops. Transforming into food. Transporting and selling. Consuming	Nutrition, health, income	Material
	Non-timber forest products	Harvesting (fishing, hunting, collecting mushrooms or medicinal plants). Transforming (preparing herbal teas, cooking). Consuming (eating, drinking).	Nutrition, health, income	Material
	Pasture production for cheese	Harvesting fodder (by humans or by cattle grazing). Storing fodder (to buffer natural seasonal variations). Milking cows. Transforming milk into cheese. Selling. Eating	Nutrition, health, income	Material
	Drinking water supply	Harvesting with buckets, wells, or pumps. Storing water in reservoirs (to buffer natural variations). Filtering and treating water. Distributing to users. Drinking.	Health, hygiene	Material
	Energy from biomass	Generating heat in a fireplace, a heater. Heating houses	Comfort	Material
Congestion NCP: Up to a certain level, human actions increase outputs (non-rivalry); beyond which they decrease output (congestion)	Scenic beauty, Recreation	Visiting a place. Watching a landscape. Swimming. Hiking. Appreciating scenic beauty.	Satisfaction, inspiration, physical health, mental well-being	Non-material
Non-rival NCP: more human actions increase outputs	Memories, images, feeling of nature	Communicating (telling stories, filming, broadcasting). Imagining. Dreaming. Remembering a nice landscape. Appreciating a nice video of nature. Giving meaning.	Identity, sense of place	Non-material

users decrease overall benefits. In the case of recreation or scenic beauty, it means that, when more people are visiting a scenic place (i.e. more co-production actions), the experience becomes less enjoyable (i.e. less realized NCP). This applies to the non-material NCP that require physical access and not to others (e.g. broadcasting videos about iconic species does not lead to congestion).

6. Substitutability and complementarity between natural and anthropogenic inputs in co-production

Substitution and complementarity are core elements of production theory in neoclassical economics, which sometimes assumes that the substitution of one resource for another is technically feasible (Cleveland et al. 1996). Some empirical works on substitutability in economics have reached the contrasting conclusions that natural and anthropogenic capitals are either substitutes or complements in production (see examples by Decker and Wohar (2012)). Other studies have suggested that neither substitutability nor complementarity have been supported by reliable empirical evidence (Van Den Bergh 1999; Rouhi Rad et al. 2021). A spectrum between substitutability and complementarity has been proposed to move beyond a dichotomous view (Cleveland et al. 1996).

In ecological economics, substitution is at the core of discussion on sustainability (Cleveland et al. 1996). 'Weak sustainability' perspectives consider high substitutability between natural and anthropogenic inputs, facilitated in particular by technological progress (Gutés 1996). These perspective have been criticized by 'strong sustainability' proponents because nature provides life support that cannot be substituted, such as water and a stable climate, and because of nature's intrinsic value, which would be lost in a substitution process (Van Den Bergh 1999; Ayres et al. 2001; Cohen et al. 2019).

Based on the description of co-production mechanisms on the previous sections and other analyses of substitutability and complementarity in co-production (Rieb et al. 2023), we posit that a main difference between NCP co-production at ecosystem (CPE) and flow (CPF) levels lies in the substitutability or complementarity between natural and anthropogenic inputs. We put forward the following propositions: (1) as CPE is about influencing natural structures and processes to enhance potential NCP, anthropogenic inputs can partially substitute for natural inputs in CPE; (2) as CPF is about converting potential NCP into realized NCP and quality of life, anthropogenic inputs complement natural inputs in CPF.

The two following sections describe the types of substitutability and complementarity in CPE and CPF and illustrate them with examples of isoquant maps (Figures 3 and 4), which are commonly used in economics and co-production studies (Rieb et al. 2023). An isoquant (represented with black line in the figures) shows the different combinations of inputs that produce the same output; an isoquant map shows several isoquants at different levels of outputs (represented with gradients from light to dark green in the figures). Our isoquant maps are built for six stylized examples, which are described as narratives, then converted into equations, which are used to draw the isoquant maps.

6.1. Substitutability in CPE

At the ecosystem level, there is some degree of substitutability between human actions and natural inputs in the co-production of potential NCP: increasing one input can compensate for a decrease in the other to produce the same amount of potential NCP. For example, humans can apply fertilizers to agricultural land to compensate for low soil fertility, while good natural soil fertility can reduce the dependence on artificial fertilizers (see discussion for a critical view on the implications of this example for sustainability)

However, this substitutability is partial because human actions cannot fully substitute for natural inputs (which can be called 'substitutability with essential natural inputs') (see Figure 3 where plots A and B are unrealistic because they ignore that natural inputs are essential). For example, without a minimum of soil capital, the application of artificial fertilizers would not enable crop production. In highly technological systems (e.g. hydroponic food production in indoor farms, where plants are grown in a nutrient solution rather than in soil), natural inputs are limited but still exist (e.g. photosynthesis and plant growth). Another example of substitution is natural tree regeneration (natural input) and tree planting (anthropogenic input): both lead to wood production and are partly substitutable but NCP cannot be produced without natural inputs (plant growth).

6.2. Complementarity in CPF

At the flow level, human actions ensure a necessary conversion of potential NCP into benefits for people and are complementary to potential NCP. As human actions and potential NCP play different roles, both are needed to produce realized NCP and quality of life. It means that the short supply of one input limits the production of realized NCP, without the possibility of using more of the other

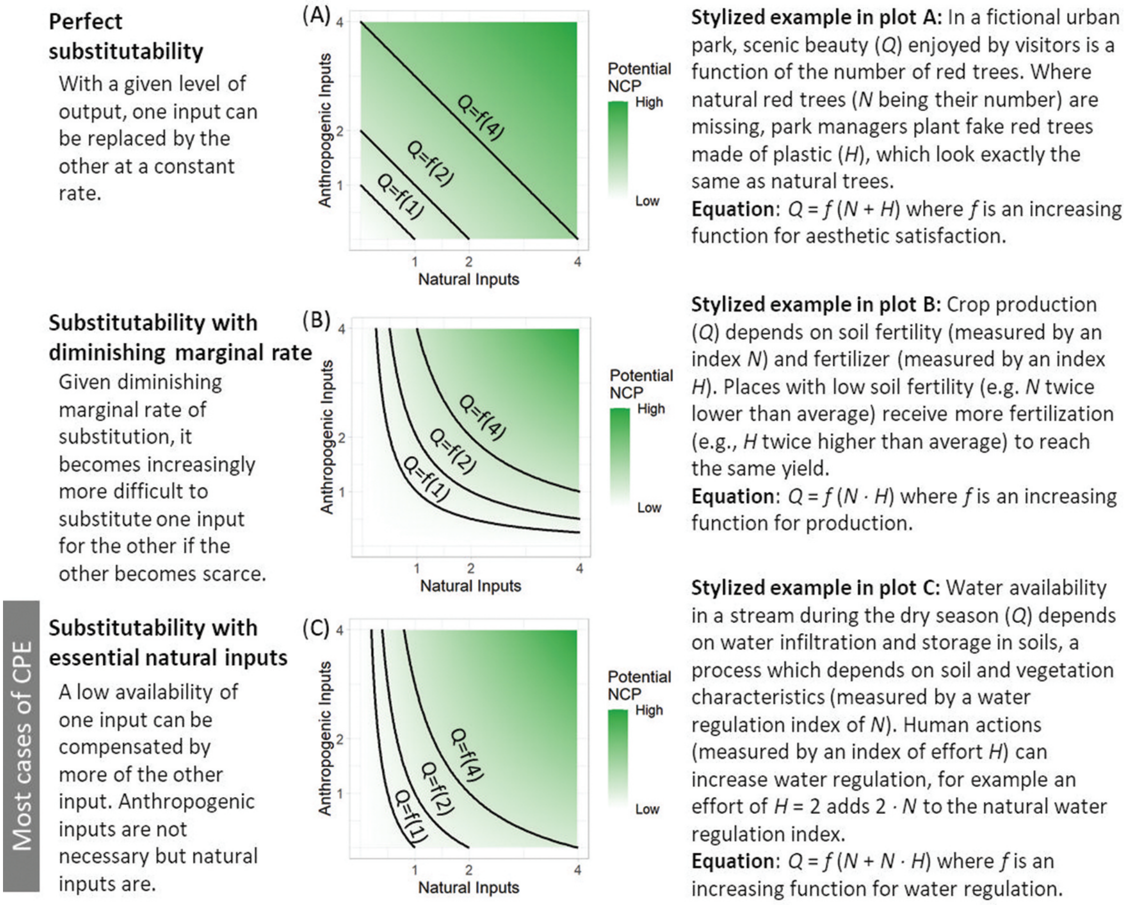

Figure 3. Isoquant maps showing three different types of substitutability between natural and anthropogenic inputs in co-production at the ecosystem level (CPE). The most common cases of CPE involve substitutability with essential natural inputs, as argued in the text. This figure uses dots as multiplication symbols.

inputs to compensate (Kraev 2002; Knoblach and Stöckl 2020). An example of complementarity is mushroom availability in a forest (natural input) and human harvesting efforts (anthropogenic inputs), which are both are needed: a low availability of either mushrooms or harvesters limits the quantity of harvested mushrooms (Figure 4(d)).

This complementarity comes with some degree of substitutability (which we can call 'complementarity with some substitution'): human actions can be increased to compensate partially for the decrease of potential NCP, for example more efforts in the transformation of crops into food can compensate for low harvest. Mushroom scarcity can be compensated, only partially, by more anthropogenic inputs (e.g. more time and better searching skills), whereas mushroom abundance can partially compensate for low human harvesting capacity (as it is easier to collect mushroom if they are abundant) (Figure 4(e)).

7. Empirical case studies

For illustration purposes, we built four co-production isoquant maps from selected empirical data (Figure 5), with two examples of CPE in agriculture (Oldfield et al. 2019) and two of CPF in recreation (Brander et al. 2007; Schägner et al. 2018) (details in Table 3). Selection of examples was constrained by the scarcity of studies that quantified variables for natural inputs, anthropogenic inputs, and NCP levels.

The isoquant maps representing co-production in the four examples have different shapes (Figure 5). For irrigated crops (Figure 5(h)), the isoquants resemble the case of substitutability with essential natural inputs (Figure 3(c)). Their verticality shows the greater importance of natural inputs than of anthropogenic inputs. For fertilized crops (Figure 5 (g)), the slopes of isoquants show a greater influence of anthropogenic inputs. Their shapes at the top of the plot show that, at a high fertilization rate, additional fertilizer tends to decrease outputs.

The isoquants for recreation in Europe (Figure 5 (i)) are similar to the complementarity case with very limited substitution (between Figure 4(d,e)). Anthropogenic inputs are very influential on the level of outputs. Natural inputs have limited effects on the outputs once a minimum level is ensured. For recreation on reefs (Figure 5(j)), the presence of asymptotes (i.e. isoquants not reaching the axis) reflects complementarity, but some substitutability is shown by the curved isoquants.

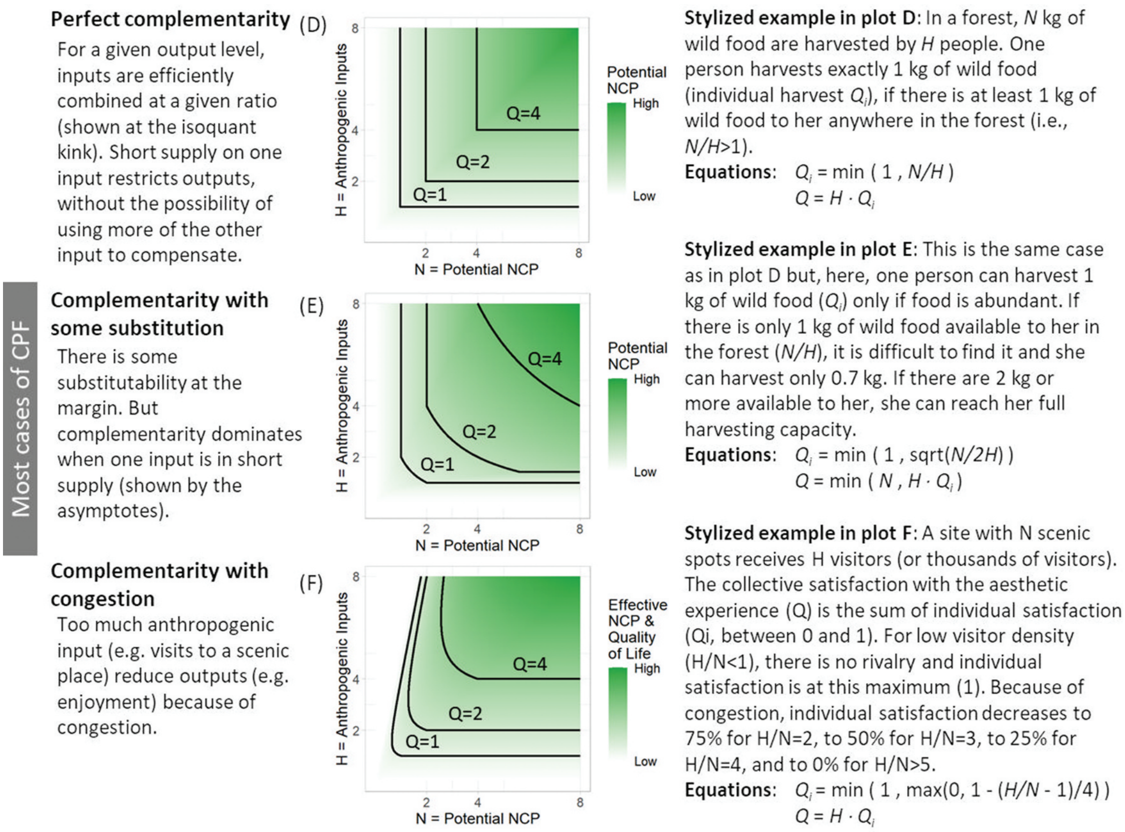

Figure 4. Isoquant maps showing three types of complementarity between natural and anthropogenic inputs in co-production at the flow level (CPF). The most common cases of CPF involve complementarity with some substitution, as argued in the text. This figure uses dots as multiplication symbols.

8. Discussion

In this paper we have produced a simple framework to better understand NCP co-production mechanisms. One novelty of the framework is the distinction between co-production at the ecosystem and the flow levels, which allowed us to show that their co-production mechanisms are fundamentally different. Our analysis found that NCP co-production at the ecosystem level generally involves partial substitutability of human and natural inputs, with essential natural inputs, whereas NCP co-production at the flow level involves mostly complementarity between inputs, with some substitution at the margin.

8.1. Limitations and critical perspectives on co-production

Although we disentangled co-production mechanisms at ecosystem and flow levels, we acknowledge that co-production at each level is still an aggregation of several co-production mechanisms (e.g. bringing agricultural knowledge, irrigation and fertilization for CPE in agriculture), as multiple human actions interact with multiple natural inputs. This aggregate treatment of mechanisms may overlook the diversity of relationships and possible explanations of outcomes (Van Den Bergh 1999). In addition, aggregation also occurs between both processes (e.g. a natural function such as photosynthesis and a human action such as planting) and capitals (e.g. natural stocks such as biomass or soil nutrients and anthropogenic assets such as workforce or tools). For example, the natural inputs to crop production include, among others, soil fertility and physiological processes of plant growth, which are both multidimensional. Future research could further disentangle co-production mechanisms per input type.

Our work illustrated a range of co-production functions with isoquants (Figures 3–5), using quantitative analyses of stylized examples and empirical data from published examples. Still, future research could identify a more diverse set of production functions from empirical case studies, for example those proposed by Rieb et al. (2017). However, quantitative analysis could be challenging because of the multiple ways of quantifying inputs and outputs. For example, in ecological economics, the discussion on the degree of substitution between human and natural capital has often remained abstract because of quantification challenges (Van Den Bergh 1999). Another challenge lies in the difficulty of separating human and natural inputs (Grosinger et al. 2021). For example, where to draw the line to measure 'natural' soil fertility of

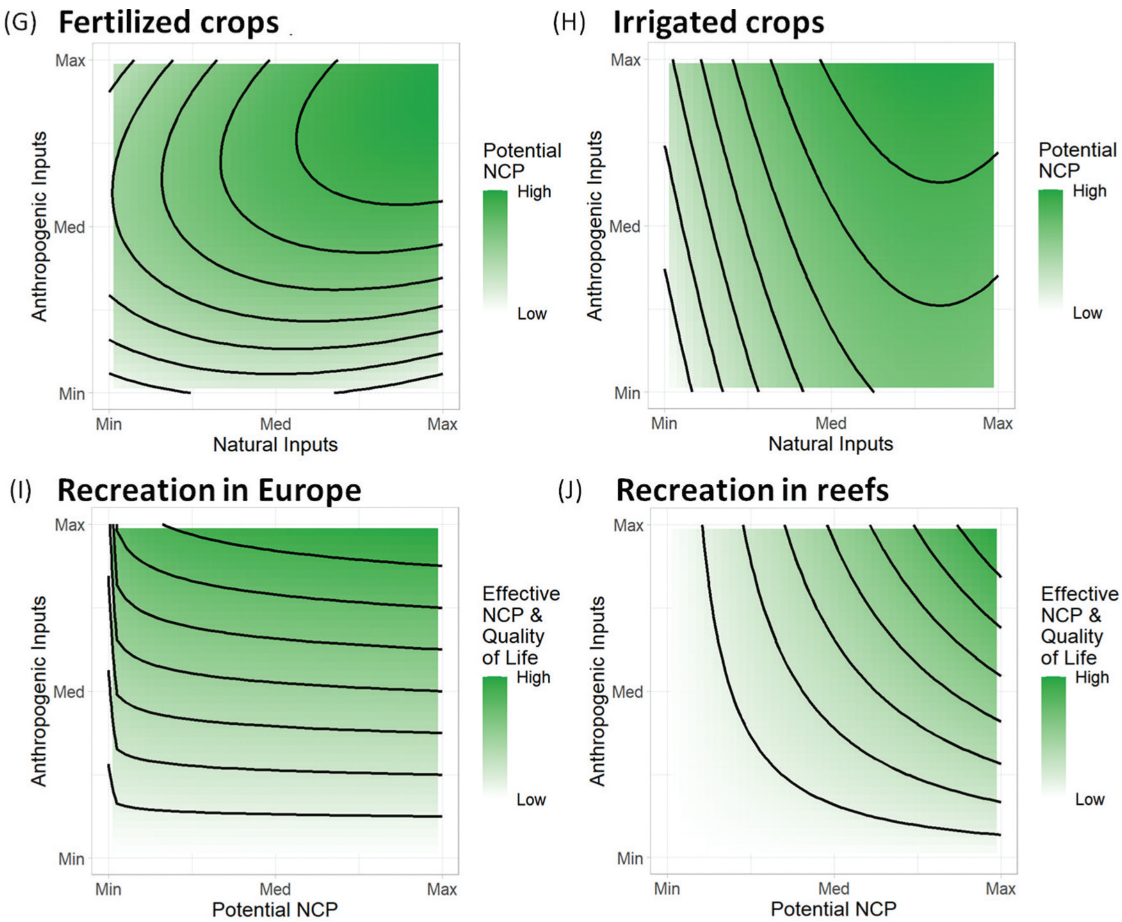

Figure 5. Isoquant maps with natural inputs in x-axis and anthropogenic inputs in y-axis for NCP co-production using data from empirical studies (see details in Table 3). An isoquant (black line) shows the different combinations of inputs that produce the same output; an isoquant map shows several isoquants at different levels of output.

a soil that has received manure or synthetic fertilizers for long periods? Or to disentangle human and natural inputs in vegetation cover managed to control erosion or in a landscape of planted hedgerows that provide pollination and pest control?

Our representation of NCP co-production presents similarities with production functions in economics (Heathfield and Wibe 2016), or ecological production functions (for the ecosystem level) and socioeconomic utility functions (for the flow level) (Mandle et al. 2021). This perspective on NCP co-production can be criticized for its reductionism, as it likens a social-ecological system to a simple factory production system, analysed in economic terms as a stable, predictable, and controllable system. The system is then described by a simple function that summarizes how inputs lead to outputs and that can be used to manage stocks and flows in that system. Whereas input substitution is reversible in a simple factory, it is unclear how easily NCP co-production inputs can be modified to move along the isoquants in any direction (Figure 3) or whether irreversibility or thresholds might occur and restrict future options (Rieb et al. 2017). More generally, the economic formalization of co-production and the substitutability between natural and human-made inputs can be criticized for their alignment with a weak sustainability perspective, which assumes that the depletion of natural resources can be offset by human-made inputs, disregarding the unique values of natural capital that would be forfeited in a substitution process (Hopwood et al. 2005).

Adopting a critical perspective and taking a normative stance on co-production are imperative because not all forms of co-production are sustainable, as evidenced by various examples. The idea of substitutability between natural and anthropogenic inputs introduces the risk that, in instances of natural capital degradation, human interventions may escalate to sustain NCP supply without addressing the root causes of degradation. For example, this could manifest as an increased use of synthetic fertilizers instead of prioritizing soil restoration and conservation. Additionally, there is the risk that human interventions aimed at maintaining specific NCP may exacerbate sustainability challenges, for example, with synthetic fertilizers contributing to water pollution. Going beyond a neutral analysis, adopting a normative perspective becomes essential for delineating strategies that promote sustainable co-

Table 3. Selected empirical case studies of co-production.

Case	Co-production level	NCP (Category)	Data source	NCP indicator	Natural input indicator	Anthro-pogenic input indicator	Source
Agriculture: fertilized crops	CPE (ecosystem)	Food crops (material)	Meta-analysis on maize and wheat yields under fertilization ($n = 840$ observation points in 29 countries)	Yield (t/ha)	SOC (soil organic content), standardized values	Fertilizer (nitrogen inputs in (kg/ha)	Oldfield et al. (2019)
Agriculture: Irrigated crops	CPE (ecosystem)	Food crops (material)	Meta-analysis on maize and wheat yields under irrigation (same as above)	Yield (t/ha)	SOC (soil organic content), standardized values	Irrigation index (from 0 not irrigated to 1 fully irrigated)	Oldfield et al. (2019)
Recreation in Europe	CPF (flow)	Recreational values (non-Material)	Meta-analysis of monetary values of recreation ($n = 245$ estimates for 147 nature areas in Europe)	Economic value of recreation (€)	Extension of nature area (ha)	Number of visitors	Schägner et al. (2018)
Recreation on reefs	CPF (flow)	Recreational values (non-Material)	Meta-analysis of economic values of recreation in coral reefs ($n = 100$ values from 52 sites)	Economic value of recreation (US$)	Area of diving site (ha)	Number of visitors	Brander et al. (2007)

production. This perspective is relevant to many current sustainability debates and policies: for example, what is a sustainable co-production of forest landscape restoration (Stanturf and Mansourian 2020) or nature-based solutions (Seddon et al. 2020)?

8.2. Implications of co-production analysis for sustainability

Our analysis of complementarity and substitutability in co-production has implications on decision-making. At the *level of NCP flow*, the identified complementarity shows that human actions can maximize benefits of NCP and quality of life, without using more resources or degrading ecosystems. One key strategy at the flow level is to improve the non-material benefits from nature, for example through aesthetic experiences, recreation, and reconnecting people to nature. The experiential, cognitive, emotional and philosophical connections are part of the co-production of NCP and can be powerful levers to help transform society towards sustainability (Ives et al. 2018; Gaston et al. 2020).

At the *level of ecosystems*, recognizing substitutability between human and natural inputs should not hide the potential for using anthropogenic inputs to restore ecosystems. Indeed, this substitutability can have two different interpretations and implications. On the one hand, it can imply an investment in anthropogenic inputs to compensate for the degradation of ecosystems, with the objective of coping with low levels of natural inputs, as in the example of the application of synthetic fertilizers to compensate for low soil fertility. On the other hand, it can imply the need to invest anthropogenic co-production inputs in restoring degraded ecosystems. For example, planting trees is a way to cope in the short term with the low level of natural tree regeneration but it is also a means to recreate the conditions for natural tree regeneration in the longer term (e.g. through the presence of seed sources, creation of a forest microclimate and soil improvement) (Marshall et al. 2023). Thus, the substitutability between anthropogenic and natural inputs is not always a replacement of nature by anthropogenic inputs, it also represents a contribution of anthropogenic inputs to the restoration of natural capital. There is a temporal dimension in co-production and substitutability: a strategy of coping with a lack of natural capital with increased anthropogenic inputs may not work for long, as for example in the cases where human-made inputs cannot be maintained over time because of their high costs. A longer-term strategy would be to rely on the substitutability of anthropogenic inputs for natural inputs with the objective of restoring natural capital rather than expanding anthropogenic capital itself (Tedesco et al. 2023). More research is needed on the interactions between natural and anthropogenic capitals in co-production and on how human-made inputs can co-produce NCP while restoring or enhancing natural capital.

Analyses of NCP co-production can support ecosystem and landscape management decisions and the search for optimal co-production strategies given natural constraints and human contexts (Rieb et al. 2023). They can identify the best use and management of natural inputs to contribute to a good quality of life, or the best use of human inputs that interact with natural capitals. Decisions can be about the actions in which to invest efforts to improve NCP and quality of life, either in managing ecosystems or in enhancing NCP flows. In this sense, a co-production analysis can help reframe problems and broaden the solution space by including diverse activities along NCP flows from ecosystems to society.

An analysis of co-production mechanisms and consequences is able to reveal adverse effects and trade-offs and the related sustainability challenges

(Rieb et al. 2023). For example, an agricultural system with high levels of CPE co-production through fertilizing inputs could pollute water. Thus, ecosystem services assessments should not just quantify ecosystem service flows, but also the co-production processes underpinning these flows to evaluate potential trade-offs (Palomo et al. 2016). To understand trade-offs, we need to analyse human actions involved in NCP co-production and their consequences: for example, the consequences of recreation activities in a forest (CPF) on forest management (CPE) and biodiversity or the consequences of soil fertilization for crop production (CPE) on another NCP such as water quality. A question that deserves further research is whether trade-offs increase with the use of manufactured capital in NCP co-production. This also relates to the ways we govern co-production processes and favour certain anthropogenic inputs.

Analyses of NCP co-production can help explore the complexity of social-ecological systems and their dynamics. This is particularly relevant for making decisions on adaptation to climate change, because NCP co-production can be dynamically adjusted as climate change unfolds. Because climate change may create novel ecosystems and novel NCP, there will be a need to imagine new forms of co-production (Lavorel et al. 2019). Examples of adjustments in co-production include new transformation and commercialization activities (CPF) to increase the diversification of rural livelihoods and make them more resilient to climate variations; the creation of biodiverse agroforestry systems (CPE) that are less vulnerable to droughts; or the restoration of forests in watersheds (CPE) to reduce floods and landslides (Pramova et al. 2012).

Our co-production framework and its co-production functions can be useful for modelling NCP. As shown by Rieb et al. (2017), one crucial research frontier for building relevant decision-support tools for NCP is to integrate the role of different types of capital in NCP provision. Our analyses can contribute to NCP models that represent the roles of anthropogenic and natural complements and substitutes. Improved models could help decision-makers assess different mixes of investments in ecosystem management or infrastructure to maximise nature’s benefits.

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Author contributions

BL, EMB, MRFL and SL participated in initial conceptualization. All authors contributed to further conceptualization, article review and editing. BL performed the formal analysis and wrote the first draft.

ORCID

Bruno Locatelli http://orcid.org/0000-0003-2983-1644

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