Received: 8 November 2022 | Accepted: 3 April 2023

DOI: 10.1002/pan3.10493

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

REVIEW AND SYNTHESIS

Co-production of nature's contributions to people: What evidence is out there?

Jana Kachler[1,2,3] | Roman Isaac[4] | Berta Martín-López[4] | Aletta Bonn[1,2,3] | María R. Felipe-Lucia[1,2,5]

[1]Helmholtz Centre for Environmental Research–UFZ, Department of Ecosystem Services, Leipzig, Germany

[2]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany

[3]Institute of Biodiversity, Friedrich Schiller University Jena, Jena, Germany

[4]Social-Ecological Systems Institute, Leuphana University of Lüneburg, Lüneburg, Germany

[5]Pyrenean Institute of Ecology (IPE-CSIC), Huesca, Spain

Correspondence
Jana Kachler
Email: jana.kachler@ufz.de

Funding information
Deutsche Forschungsgemeinschaft, Grant/Award Number: DFG-FZT 118, 202548816; DFG Priority Program 1374 "Biodiversity Exploratories", Grant/Award Number: 433163377

Handling Editor: Emmeline Topp

Abstract

1. Nature's contributions to people (NCP) rarely originate from nature alone. Often, only by joining natural capital with forms of anthropogenic capital, NCP emerge benefitting people. Understanding how NCP are co-produced by natural and anthropogenic capitals is needed to inform decision-making on sustainable land-use practices.
2. Through a systematic review of the literature, we compile existing empirical evidence on NCP co-production and how this evidence was arrived at. We identified 237 observations from 25 publications on anthropogenic capital indicators co-producing NCP. The reviewed studies were conducted mainly in cropland and forest ecosystems and at the landscape level.
3. Our results show that most evidence for co-production exists for material NCP, with physical capital and/or human capital as main input. Interestingly, non-material NCP relied mostly on human or social capital only, while material and regulating NCP involved multiple types of anthropogenic capital.
4. Our findings provide guidance for future research on how to explicitly incorporate NCP co-production to analytically assess the relationships between anthropogenic capitals and NCP provision.

KEYWORDS
anthropogenic assets, coproduction, ecosystem services, nature's contributions to people

1 | INTRODUCTION

Nature's contributions to people (NCP) are fundamental for human life (Hill et al., 2021). Since the launch of the Millennium Ecosystem Assessment (2005), a vast amount of studies on NCP, ecosystem services, and related concepts has been published, mostly focusing on ways to value and map their supply (Schröter et al., 2021). Most of these studies assume that nature generates benefits for people while neglecting the contributions of human activities and other forms of anthropogenic capital to their co-production. Recent literature highlights that NCP are not solely nature-given but mostly co-produced by a combination of both natural and anthropogenic capitals (Cook et al., 2020; Dvarskas, 2018; Lavorel et al., 2020; Pérez-Soba Aguilar et al., 2019). Co-production refers to "a process through which inputs from individuals who are not 'in' the same organisation are transformed into goods and services" (Ostrom, 1996, p. 1073). We define co-production here as the joint contribution of natural and anthropogenic capitals that generates material, regulating, and non-material NCP (Díaz et al., 2015; Figure 1). The idea of co-production has been operationalised in the science-policy

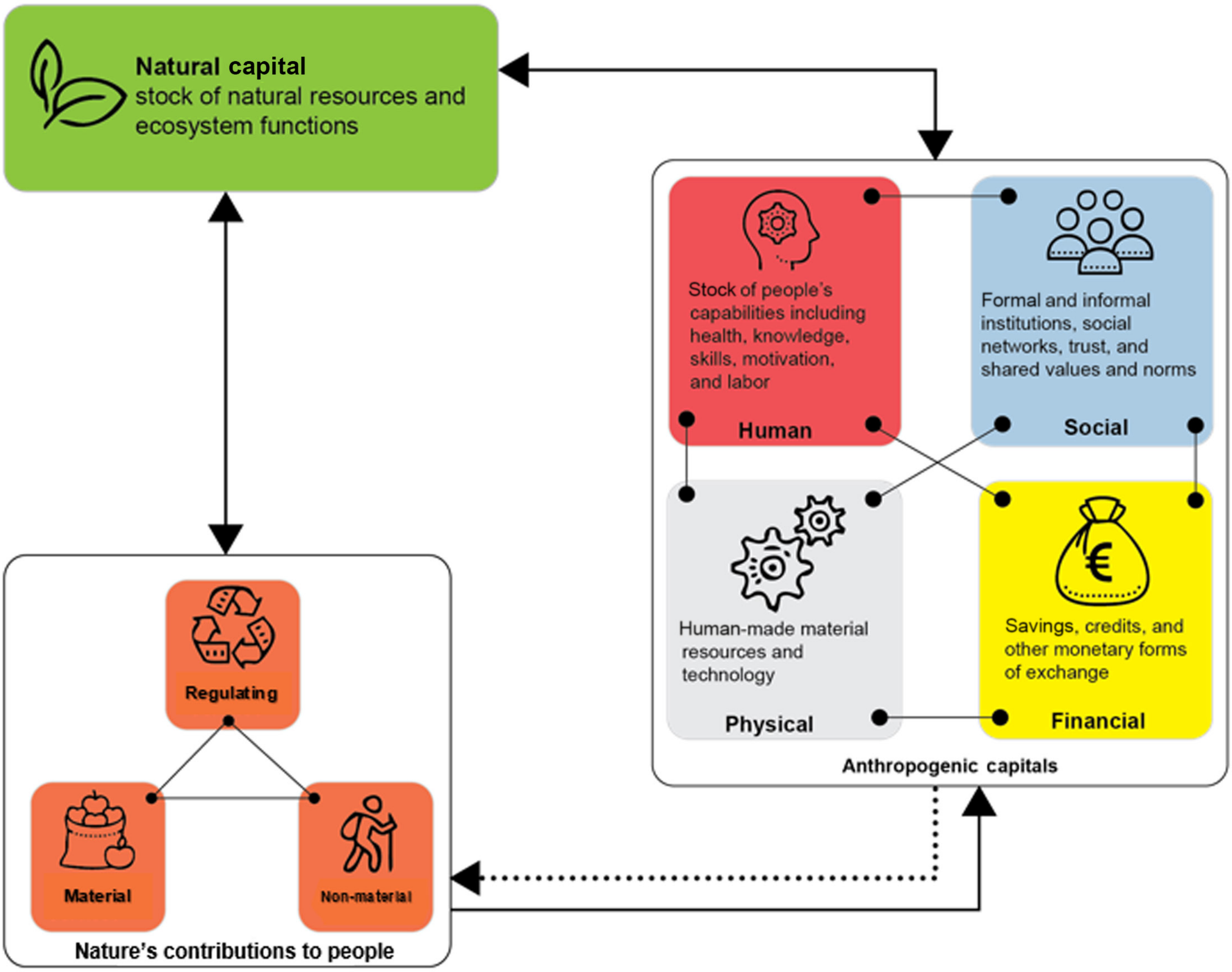

FIGURE 1 Framework on nature's contributions to people (NCP) co-production depicting the interplay of natural and anthropogenic (human, social, physical, and financial) capitals providing material, regulating, and non-material NCP. This interplay also creates synergies and trade-offs among NCP and feedback from NCP to natural and anthropogenic capitals. Note that in this review we only look at the relationship of the direction from anthropogenic capital to NCP (arrow with dashed line). Adapted from Díaz et al., 2018 and Palomo et al., 2016.

interface arena by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

The IPBES' conceptual framework around nature's contributions to people highlights human and nature interactions and emphasises the essential role of anthropogenic capital in mediating the provision of nature's benefits to people (Hill et al., 2021; Kadykalo et al., 2019). This framework extends the ecologically and economically coined concept of ecosystem services by adding an emphasis on social, institutional, and cultural issues (Dean et al., 2021). Thus, it expands epistemological boundaries (Dean et al., 2021; Díaz et al., 2018; Kadykalo et al., 2019) within which we place the conceptual framework of our literature review. Using this framework, we adhere to the concept of NCP in this literature review and acknowledge that NCP contribute to human well-being or quality of life in various ways. Material NCP refer to all material contributions (i.e. products, substances, or material elements) directly nourishing or supporting people. Regulating NCP refer to environmental processes and functions contributing to human well-being, for example, through pollination and hazard mitigation. Non-material NCP refer to people's subjective or psychological experience of nature, both individually and collectively, for example, by getting inspired by nature (Bhattacharjee et al., 2022; Díaz et al., 2018). Anthropogenic capitals, also termed anthropogenic assets (Palomo et al., 2016), refer to "built infrastructure, health facilities, knowledge (including [indigenous and local knowledge systems], and technical or scientific knowledge, as well as formal and non-formal education), technology (both physical objects and procedures), and financial assets among others" (Díaz et al., 2015, p. 5). Natural capital refers to the stock of natural resources and ecosystem functions. Anthropogenic capital comprises human, social, physical and financial capital (see Box 1 for definitions).

There is little empirical evidence on the role of different combinations of natural and anthropogenic capitals in sustainability (Bennett

BOX 1 Definitions of Capitals Based on Goodwin (2003), Palomo et al. (2016) and Pretty and Bharucha (2014)

Natural capital: stock of natural resources and ecosystem functions that independently or combined with anthropogenic capitals provide goods and services for human well-being.

Human capital: stock of people's capabilities including health, local knowledge, formal knowledge, skills, motivation and labour contributing to the provision and use of NCP.

Social capital: (in)formal networks, trust, shared values, and norms contributing to the provision and use of NCP.

Physical capital: human-made material resources and technology that contribute to the provision and use of NCP.

Financial capital: virtual mechanisms in the form of savings, credits, and other monetary forms used for trading, maintaining, or enhancing natural, human, social, or physical capitals in the provision and use of NCP.

et al., 2021; Palliwoda et al., 2021; Setten & Brown, 2018). This gap needs to be filled, as NCP co-production provides the framework to achieve more sustainable landscape management and policy making by understanding the biophysical and human factors that jointly underpin NCP provision (Henriksson Malinga et al., 2018; Torralba et al., 2018).

Co-production can broadly be seen in two ways: (1) the physical mobilisation of natural and anthropogenic capitals in the provision of NCP, and (2) the cognitive process inherent to humans in the appreciation of NCP (Lavorel et al., 2020). It is thus differentiated, as Fischer and Eastwood (2016) put it, between the making of *things* and the making of *meaning*. For example, physical processes can be observed in agricultural material intensification that makes use of irrigation, fertilisers, biocides and mechanisation to manage existing lands more productively (Foley et al., 2011). Cognitive processes become apparent when considering activities that are strongly driven by knowledge, skills, preferences and motivations, such as particular forest management or conservation actions (Bruley et al., 2021). Non-material NCP, in particular, are recognised to arise from social-ecological interactions with intangible human contributions (Chan, Guerry, et al., 2012; Chan, Satterfield, & Goldstein, 2012).

Often, co-production is a mixture of both physical and cognitive processes. For example, appreciation of nature's beauty can be not only the result of cognitive or psychological processes inherent in individuals, but also physical management practices, such as tourism infrastructure or making the landscape accessible (Palomo et al., 2016).

Furthermore, the interplay of natural and anthropogenic capital has opportunities to enhance multiple NCP, but it also risks generating certain NCP at the cost of others (Felipe-Lucia et al., 2014; Lee & Lautenbach, 2016). On the one hand, knowledge on co-production has the potential to create synergies: situations in which multiple NCP co-vary positively (Mouchet et al., 2014). For example, traditional small-scale farming provides food and non-material cultural values at the same time (Auer et al., 2017). On the other hand, knowledge on anthropogenic capital inputs can help assess and evaluate potential trade-offs: situations when, due to certain capital input, one service increases and others decrease or when one stakeholder benefits more from an NCP at the expense of other stakeholders (Bennett et al., 2021; Howe et al., 2014; Palomo et al., 2016). For example, new crop varieties and livestock breeds in combination with increased use of mineral fertiliser, pesticides, and machinery can substantially increase food production while depleting groundwater for freshwater supply or irrigation, affecting pollinators and other beneficial insects (Pretty & Bharucha, 2014).

Therefore, to manage multifunctional landscapes, we need to better understand the interactions of natural and anthropogenic capital in agricultural systems and how they can result in multiple NCP (Bennett et al., 2021). To do so, it is critical to understand which NCP can be best co-produced with different forms of capital and actively promote synergies through management practices (Felipe-Lucia et al., 2018; Palomo et al., 2016).

Moreover, the input of different forms of anthropogenic capital may negatively affect natural capital, e.g., when agricultural ecosystems and their biodiversity are negatively impacted by fertilisers or biocides, eventually leading also to a loss of NCP. This loss might be recovered by further anthropogenic and natural capital input. For instance, when pesticide use has resulted in a decrease of local pollinator populations, the land-user might establish nectar-rich flower strips or conserve non-crop habitats to support pollinators (Bianchi et al., 2013).

To comprehend how co-production has been identified in NCP and ecosystem services research, we conducted a systematic literature review of all empirical studies in this research field following the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al., 2009).

As the scientific literature on co-production has barely been operationalised (Bruley et al., 2021; Palliwoda et al., 2021) we expect that only a few publications have explicitly included this concept in their study design. We expect to find more evidence for the co-production of material and non-material NCP based on the assumption that regulating NCP are generated mostly by natural capital rather than by anthropogenic input (Spangenberg et al., 2014). We hypothesise that a larger share of observations will involve physical capital compared to inputs of human, social, or financial capital. This is because material inputs such as fertilisers can be measured more easily than intangible factors such as the experience of land users or institutional conditions. Most non-material NCP depend on a genuine experience of nature (Rieb et al., 2017) or influences of the media and its content on human-nature interactions (Silk et al., 2021). Based on the assumption that these NCP are generated through cognitive processes inherent to individuals and that interactions with nature may be shaped by formal or informal rules

(Spangenberg et al., 2014), we hypothesise that non-material NCP involve foremost human and social capital.

In order to assess existing evidence in the literature on co-production of NCP, this systematic review aims to identify (1) how co-production is defined and operationalised in the NCP and ecosystem services literature and (2) which constellations of natural and anthropogenic capitals underpin material, regulating and non-material NCP, as well as synergies and trade-offs between NCP. On the basis of our findings, we provide an outlook for an agenda to advance this emerging research field.

2 | METHODS

We used the Web of Science engine for the search, including publications that reported original case studies (i.e. excluding literature reviews or theoretical work) published in English that (1) analysed NCP or ecosystem services, (2) their provision, supply, demand, use or value, and (3) explicitly or implicitly used indicators of anthropogenic capitals and linked them to NCP. For each of these criteria, we developed a list of search words that were combined in our literature search (see Supporting Information for the complete search string). The literature search was finalised on January 1st, 2021, and resulted in the retrieval of 384 publications.

We reviewed titles, abstracts, and keywords to assess eligibility based on a set of exclusion criteria (Table 1). In this literature review, we excluded any theoretical work, non-peer-reviewed publications, or conference papers (Exclusion criterion 1). We also excluded publications based on scenarios, theories, or hypothetical work, as we wanted to retrieve empirical evidence from case studies only (Exclusion criterion 2). The publication had to include NCP indicators as well as anthropogenic capital indicators and jointly analyse them so that we could draw conclusions for co-production. Publications that included only one aspect or did not bring them together were excluded (Exclusion criteria 3–6). Furthermore, in this literature review, we only included publications in which anthropogenic capitals lead to the provision of NCP. Publications that dealt with the degradation of NCP as a result of anthropogenic capital input or focused on disservices were excluded (Exclusion criterion 7).

TABLE 1 Exclusion criteria for literature screening.

Exclusion criteria
1. Type of publication (exclude: theoretical paper/non-reviewed publication/conference paper)
2. Co-production is identified through scenarios, theories or other hypothetical means
3. Publication assesses NCP indicators but does not assess anthropogenic capital indicators
4. Publication assesses anthropogenic capitals but does not assess NCP indicators
5. Neither anthropogenic nor NCP indicators are assessed in the publication
6. The publication assesses both, anthropogenic and NCP indicators, but does not relate one to another (e.g. through multivariate statistics, regression analysis, or content analysis)
7. The publication assesses the effect of anthropogenic capitals on NCP degradation (or ecosystem disservices)

We retained 170 publications for further analysis. The concept of co-production did not have to be explicitly stated in the publications, but needed to be identifiable for two coders (JK, RI). For example, Bravo-Monroy et al. (2015) state that pollination benefits on coffee plantations are dependent on ecological and human factors (both social and economic). The authors study the effect of these factors on bee richness, abundance, and visitation frequency. Among their research implications, they state that species-rich pollinator communities that improve coffee yield can be potentially promoted by coffee farmers. Although this study does not explicitly investigate co-production, they refer to the idea of it and support the research field of co-production through their findings. In another example, Jackson et al. (2012) investigate biodiversity-based agriculture. The authors argue that ecological intensification requires investing in five key livelihood resources, which they call human, social, natural, physical, and financial assets. In their work, they describe eight different agricultural landscapes that include NCP and identify social-ecological domains that include landscape-level capital assets (i.e. financial, physical, natural, human, and social/institutional capital). Although the concept of NCP co-production was not mentioned, its framework and investigation provides eligible evidence for this review.

A full text screening to confirm alignment with our inclusion and exclusion criteria retained 16 publications for complete analysis. We added nine publications from other sources (mainly citations in literature reviews that appeared in our initial search), resulting in a total of 25 publications included in the final analysis (see Supporting Information for the full list of reviewed publications).

To standardise our analysis, we developed a codebook that includes all relevant variables and tested the coding in a pilot classification with 10 publications by four authors. After agreeing on the final codebook (Table S1), we coded the information from each study in two separate databases.

The first database contained information on (1) the general data from the studies (e.g. title, authors, year of publication, etc.), (2) the study area (e.g. country, type of landscape, etc.), (3) the methodological approach (e.g. type of data, type of analysis, etc.) but also (4) to what extent the study involved the concept of co-production, and (5) whether the paper analysed the supply, demand, or distribution of NCP (as defined by the authors), and synergies or trade-offs between NCP.

The second database contained information on all types of relationships between anthropogenic capitals and NCP. In this database, we incorporated as many rows per study as links between anthropogenic capitals and NCP found. For each relationship, we included information on (1) the indicator and category (material, regulating, non-material) of the NCP analysed, (2) the indicator and category of the anthropogenic capital (human, social, physical, financial) involved, and (3) the indicator and category of NCP that appeared as synergy or trade-off in this relationship. We coded NCP according to our classification (Table S1) and anthropogenic capitals according to our definitions described in Box 1. Extracting all observations reporting a linkage between at least one anthropogenic capital and one NCP resulted in 237 observations of NCP co-production. The linkages were identified depending on the analytical method used in the reviewed publication, where we distinguished between multivariate statistics, analysis of variance, regression analysis, content analysis, and synthesis. Multivariate statistics includes multiple correspondence analyses, principal component analyses and redundancy analyses. Analysis of variance includes ANOVA analyses and non-parametric tests. Regression analysis includes standard types of regression analyses and correlation tests. Content analysis refers to the direct analysis of verbatim reports. Synthesis refers to the interpretation of evidence derived from various analyses. For publications using regression analysis, principal component analysis, or other types of correlations, we coded information on significant coefficients. For publications using content analysis, we coded citations of qualitative results. Qualitative information did not have to refer to co-production directly. A verbatim or summary of multiple verbatims of the authors had to contain information on the anthropogenic capitals involved in the provision of NCP. This included results such as "our interviewees mentioned how they had, with the help of suitable machinery, produced timber from trees that had grown on the estate" (Fischer & Eastwood, 2016, p. 45). For the sake of simplicity, we refer to all our results as observations on NCP co-production.

3 | RESULTS

3.1 | General trends in NCP co-production

Our systematic search identified 25 publications that show empirical evidence of NCP co-production from a total of 384 scanned publications. The first publication with evidence on co-production was published in 2005, but the number of publications only started to increase in 2012 (Figure 2a). All publications present case study results, except for two expert reviews based on multiple case studies. Most of the publications provide evidence from Europe (24%), followed by South America (19%), Asia (19%) and Africa (19%; Figure 2b). Australia and Oceania (7%) and North America (10%) are less represented. Some publications present results from multiple continents and countries. Most studies cover a mix of different types of landscape, dominated by cropland (25%), forest (20%) and grassland (19%) (Figure 2c). Landscapes less studied are non-woody natural vegetation (9%), marine and coastal areas (8%), freshwater (6%), mountain (6%) and urban landscapes (5%).

Regarding the temporal scale, the majority of studies investigates NCP at only one point in time (88%; Figure S2a). Regarding the spatial scale, most studies analyse NCP at the landscape scale (64%; Figure S2b). Other studies provide information on a smaller scale, that is, farm (16%) or municipality (16%). There is only one study at the multi-national scale and no publication at the global, continental or national scale.

3.2 | Identification of co-production

Six publications (24%) employ the NCP co-production concept explicitly while the remaining publications do so implicitly (i.e. they do not use the term but refer to the idea in their study design or discussion). The publications dealing with the concept explicitly use similar definitions or conceptualisations but highlight the relevance of investigating NCP co-production differently.

For example, Fischer and Eastwood (2016) broadly interpret co-production as "a process that involves both human and non-human entities" (p. 43) and according to Lavorel et al. (2020) "co-production is defined as the interplay of natural and human-derived capitals for producing ecosystem services" (p. 2). Based on their findings, Fischer and Eastwood (2016) advocate for considering people's identities and capabilities in evaluations of ecosystem services, as these influence the transformation of ecosystem structures into benefits.

Lavorel et al. (2020) argue that co-production of NCP is a critical component of climate change adaptation and that ecological properties can only support adaptation through anthropogenic inputs such as knowledge, infrastructure, social capital and participation of institutions. They highlight that understanding co-production enables stakeholders to target interventions and overcome barriers to the adoption, management, and use of ecosystem services for climate adaptation.

Garcia-Llorente et al. (2012) show with their study that "ecosystem service trade-offs are determined by the joint operation of biophysical and sociocultural factors" (p. 12) demonstrating that ecosystem services are co-produced by ecosystems and social systems. The authors criticise that, instead of focusing on associations between ecosystem services, research on ecosystem services trade-offs needs to consider the biophysical and sociocultural factors that determine these trade-offs.

Henriksson Malinga et al. (2018) explain that "interactions, between the natural environment, human skills and decisions, technology and infrastructure, and socio-non-material organization and institutions, result in the coproduction of ecosystem services" (p. 1). The authors argue that the analysis of multifunctional agricultural landscapes needs to consider the factors underpinning co-production as well as the diversity of demands, values, and benefits of ecosystem services by different groups. According to the authors, this information is required to measure and reward the performance of multifunctional agricultural systems that can achieve integrated environmental, social, and economic goals.

Similarly, in the context of Spanish rangeland systems, Torralba et al. (2018) state that the co-production of ecosystem services is "based on feedback processes in which a social system actively shapes and modifies an ecosystem through farm management" (p. 2). The authors highlight that policymakers need to recognise

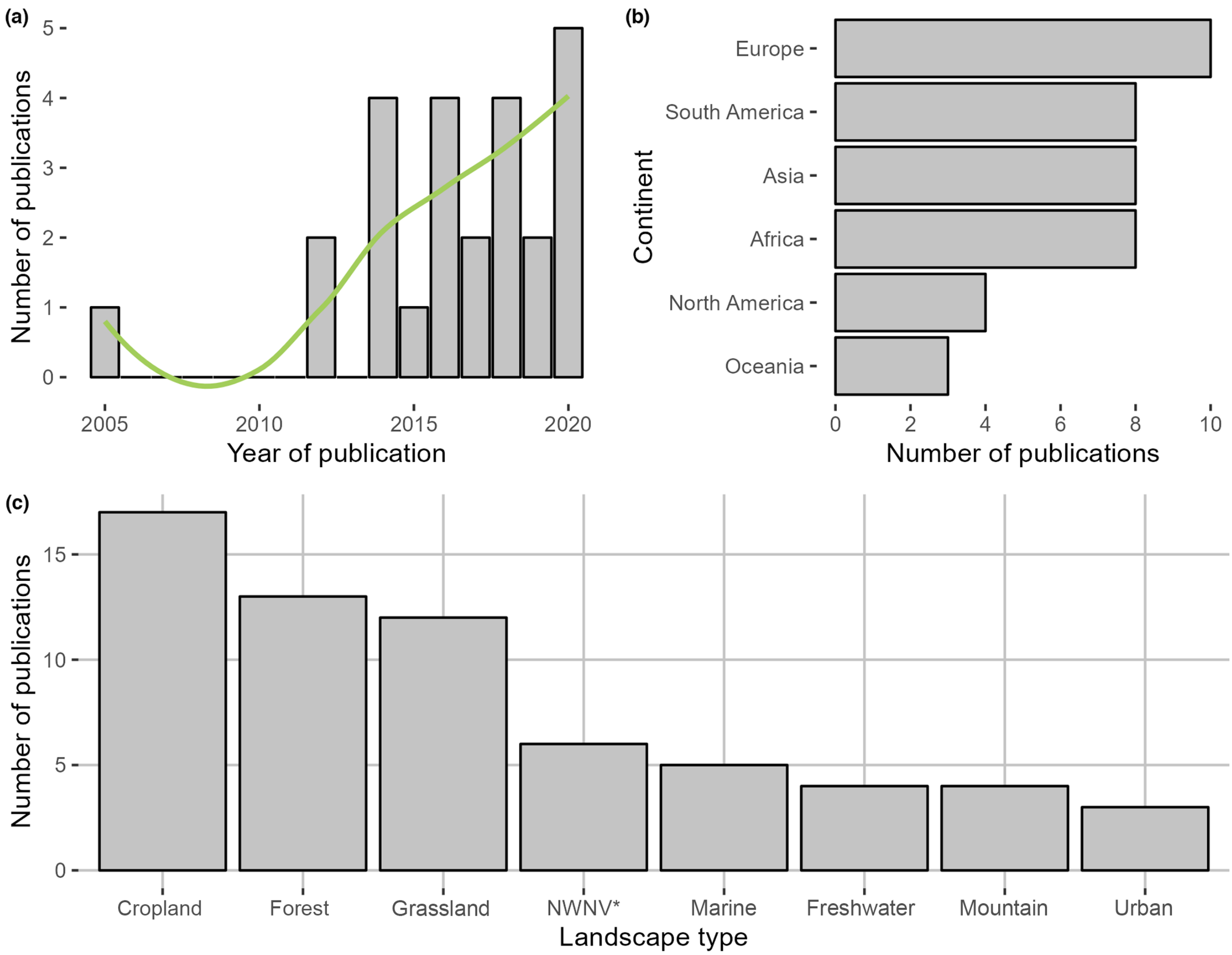

FIGURE 2 General trends in NCP and ecosystem services research addressing co-production. (a) Number of publications per year of publication (*n* = 25). (b) Number of publications per continent (can be multiple per publication; *n* = 42). (c) Number of publications per landscape studied (can be multiple landscapes per publication; *n* = 64). *NWNV, non-woody natural vegetation.

these connections to *"address the complex reality of rangeland social-ecological systems"* (p. 9). Vialatte et al. (2019) agree that landscapes are shaped by stakeholders (e.g. farmers and foresters) and their activities which directly modify ecosystems. These stakeholders are thus not only beneficiaries but also co-producers of NCP.

3.3 | NCP and anthropogenic capitals

We identified a total of 237 observations on NCP and related anthropogenic capitals. Most observations on co-production refer to material (38%), followed by non-material (33%) and regulating NCP (27%). In general, co-production most frequently involves human capital (32%), followed by physical capital (27%), and social capital (25%). Financial capital is the type of anthropogenic capital for which we found the least observations (16%).

The majority of publications are based on primary data (68%), or both primary and secondary data (24%), and only 8% use data from secondary sources (Figure S3). More studies use quantitative data (52%) than qualitative data exclusively (16%), with 32% of the publications using both quantitative and qualitative data (Figure S4). Most studies focus exclusively on the supply side of NCP (68%), followed by both supply and demand (20%) and demand of NCP (8%; Figure S4). Only one study deals with the distribution of NCP (Hicks & Cinner, 2014).

The main analytical methods used to detect co-production of NCP are content analysis (42%), analysis of variance (30%), and multivariate statistics (20%; Figure 3). Only a few observations are the result of network analysis (6%) or synthesis (2%). The majority of evidence for co-production of material and regulating NCP is derived through content analyses. The majority of evidence for co-production of non-material NCP is derived through analyses of variance. The content analysis presents the largest share of evidence for anthropogenic capitals. For observations on human and physical factors, this proportion is relatively smaller than for social and financial capital. A relatively higher amount of observations is derived through analyses of variance.

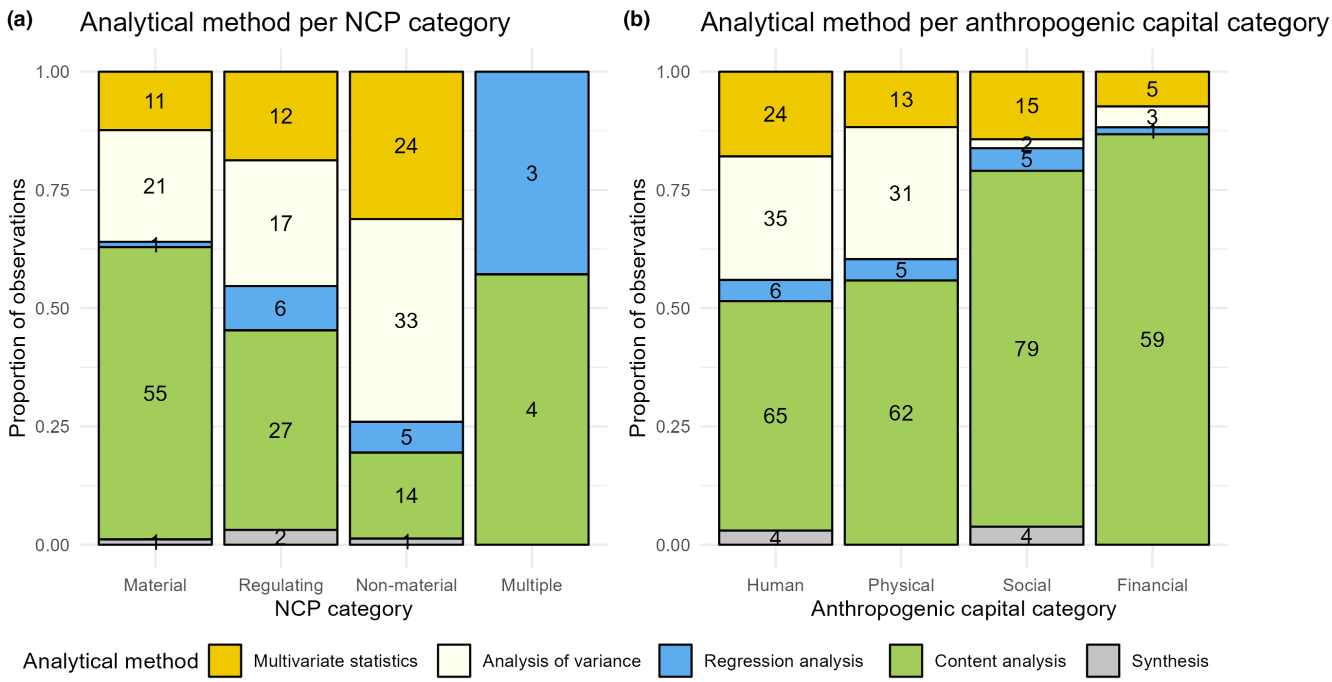

FIGURE 3 Proportion and number of observations that were derived using a particular analytical method in the reviewed publication per (a) NCP category ($n=237$) (b) anthropogenic capital category ($n=418$). *Multivariate statistics* includes multiple correspondence analyses, principal component analyses and redundancy analyses. *Analysis of variance* includes ANOVA analyses, and non-parametric tests. *Regression analysis* includes standard types of regression analyses, and correlation tests. *Content analysis* refers to the direct analysis of verbatim reports. *Synthesis* refers to the interpretation of evidence that is derived from various analyses. Note that the number of observations for anthropogenic capitals is higher as one observation for an NCP can include at least one, but often multiple anthropogenic capitals.

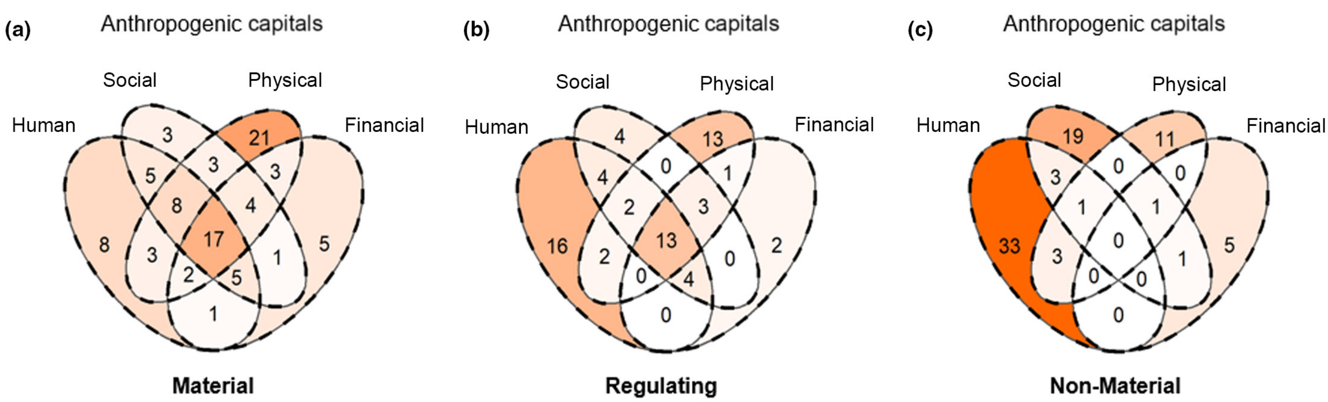

FIGURE 4 Anthropogenic capital constellations in (a) material, (b) regulating and (c) non-material nature's contributions to people (NCP). Each ellipse contains the number of observations that involve the respective anthropogenic capital type (i.e. human, social, physical and financial). Overlaps represent the number of observations that involve multiple anthropogenic capital types. The intensity of the colour shade is proportional to the relative frequency in observations for that anthropogenic capital type and NCP.

3.4 | Linking NCP and anthropogenic capitals

3.4.1 | Material NCP

Physical (69%) and human (55%) capital are most frequently presented as a single or combined input for the 89 observations on material NCP (Figure 4). This is followed by social (52%) and financial (43%) capital. The majority (58%) of observations involve a combination of anthropogenic capitals, while 42% rely uniquely on one capital type. Among the observations that include a combination of anthropogenic capitals, 77% involve physical capital, which is most frequently combined with social and human capital and, to a lesser extent, with financial capital. Noticeably, 33% of observations on combined capitals include all four types of anthropogenic capital.

Among the observations that involve only one type of anthropogenic capital (42% of total observations), the majority involve physical capital (57%) followed by human capital (22%), financial (14%), and social capital (8%; see Box 2 for examples).

BOX 2 Examples of co-production of material NCP

Cereal production in Northern Ethiopia. Zeweld et al. (2020) conduct a standardised questionnaire with 350 farmers in Northern Ethiopia. They combine observed variables such as family size or livestock density with latent variables such as relational capital in an ANOVA analysis to assess differences in these variables related to the choice of land management practises. In the next step, they apply an endogenous switching regression model to assess the average impact of agricultural practices on material NCP such as cereal yield per hectare, and per capita harvests (material NCP). Farmers who apply contour terracing only have a higher cereal yield per hectare and a higher per capita harvest. Contour terracing measures involve stone walls, soil bunds and bench terracing (physical capital). Farmers who apply organic fertiliser (physical capital) such as animal manure or other waste have a higher cereal yield per hectare and a higher per capita harvest as well. The two measures combined have a similar effect. Furthermore, the decision to adopt these practises are driven by multiple factors such as education, or family size (human capital).

Climate adaptive food systems in the Solomon Islands. Lavorel et al. (2020) focus on the co-production of NCP for climate change adaptation using five exemplary case studies across different socio-ecosystems and continents. Based on the authors' in-depth knowledge and published material they carry out a qualitative, deductive analysis to analyse co-production along three steps of the ecosystem cascade: (i) ecosystem management; (ii) mobilisation; and (iii) appropriation, social access and appreciation. One of their case-studies from the Solomon Islands shows how all four different types of anthropogenic capital are required for food production (material NCP). Here, new food production systems are based on workforce, skills, and knowledge (human capital), cohesion and collective work in the community (social capital), basic tools (physical capital), and financial aid from an NGO (financial capital) (Lavorel et al., 2020).

3.5 | Regulating NCP

In general, the 64 observations on regulating NCP show patterns comparable to those of material NCP. The number of observations with capital combinations (45%) and single capital types (55%) is relatively balanced. Human capital (64%) and physical capital (53%) capitals are most frequently presented, as a single or combined input. This is followed by social (47%) and financial (36%) capital (see Box 3 for examples).

BOX 3 Examples of co-production of regulating NCP

Pollination in Brazil. Hipólito et al. (2016) quantify pollinator richness and human, physical, social, and financial assets in 30 coffee plantations in eastern Brazil. Based on a questionnaire, the authors run generalised linear models to analyse the influence of predictor variables covering anthropogenic assets on the number of pollinator friendly practices. The authors show that pollinator richness is significantly associated with the type of work that the owner performs on the plantation. More specifically, active labour work on the plantation (human capital) rather than administration-type work explains greater pollinator-friendly practices which in turn have a significant and positive effect on flower visitor richness (regulating NCP).

Coastal NCP in the Indian Ocean. Hicks and Cinner (2014) provide an analysis of perceived coral NCP and mediating access mechanisms (rights, knowledge, economic, social and institutional) across four countries in the western Indian Ocean. Information from focus groups, semi-structured interviews, and a quantitative survey are analysed through redundancy analysis to assess how perceived NCP benefits are explained by these access mechanisms. The authors show that perceived benefits from regulating NCP (coastal protection and sanitation) are associated with better market access (social capital) and access to knowledge (human capital).

3.5.1 | Non-material NCP

Of 77 observations on non-material NCP, 52% included human, 33% social, 21% physical capital and 9% financial capital. In contrast to material NCP, most observations on non-material NCP deal with one single type of anthropogenic capital (88%). Among the nine observations on combined capitals, we found mainly human and social capital. There were only two observations that involved more than two types of capital and no observations that involved all types of anthropogenic capitals. Of the observations that involve one single type of anthropogenic capital, the majority involve human capital (49%). This is followed by social (28%), physical (16%) and financial (7%) capital (see Box 4 for examples).

3.5.2 | Synergies and trade-offs between NCP

Nine of the 237 observations involve a synergy between NCP, mainly between material and regulating NCP. For example, the application of organic manure on coffee plantations promotes pollination and coffee harvest simultaneously (Bravo-Monroy et al., 2015). Two

BOX 4 Examples of co-production of non-material NCP

Fischer and Eastwood (2016) investigate co-production of NCP on the Falkland Estate in Scotland, United Kingdom. The authors conducted loosely structured interviews with 47 respondents either living or working in or near the estate. Their results show how non-material NCP are co-produced through cognitive or tangible processes that require either social, human, or physical capital. For example, "[the interviewees] learned and benefited from other Forest users' skills and knowledge in wildlife spotting or historical insights, or simply enjoyed encountering them on their walks" (p. 45). In another example, "adjacency of one's home to the Forest (or alternatively, easily accessible and affordable transport) could also be considered as physical capital that enabled people to interact with the place in specific ways, as several interviewees emphasized how their proximity to the woodlands meant that they were going there regularly" (p. 47). According to the authors these "capabilities" (e.g. physical and financial factors, perceived rights, and confidence) enable people to co-produce ecosystem services.

Torralba et al. (2018) conducted 42 in-depth and semi-structured interviews with property owners of wooded rangelands (*dehesas*) in Spain. They carried out a hierarchical cluster and principal component analysis to identify associations between *dehesa* characterizations, ecosystem services, and land management variables. The activities hunting, recreation, outdoor activities, and wild resource harvesting (non-material NCP) could all be found in a cluster with public access, either through public paths (physical capital) or the area being part of all common land (social capital). The authors conclude that public access is the reason for the high values for cultural ecosystem services indicators (non-material NCP). The authors explain that birdwatching is one of the principal motivations to visit the study area. Public paths are often the only possibility to guarantee proximity to agricultural habitats for this main tourist attraction. The harvesting of wild resources such as asparagus and mushrooms by local inhabitants is facilitated through the *dehesa* being seen as a common space.

observations on synergies include regulating and non-material NCP, where stakeholders benefit from biological control, pollination, and landscape aesthetics simultaneously. Four of the 237 observations involve trade-offs. All observed trade-offs involve the generation of material NCP, which negatively affects material, non-material, and regulating NCP. For example, in the study by Lavelle et al. (2016) on unsustainable landscapes in the deforested Amazon, cattle production (material NCP) facilitated by formal knowledge (human capital) was found to be negatively associated with regulating soil NCP. In another example, timber and firewood production was co-produced with the support and advice of agricultural advisors (human and social capital) and formal and informal agreements with loggers (social capital) at the expense of landscape aesthetics (non-material NCP) (Vialatte et al., 2019).

4 | DISCUSSION

Humans and nature interact in a multitude of ways. Eventually, they may not even be separable. In other words, sometimes one cannot define nature without including humanity or some aspects of it (Russell et al., 2013). For example, cultural landscapes such as Mediterranean Silvio-pastoral systems provide a multitude of NCP and would not exist without humans. The management of such landscapes is based on traditional ecological knowledge (human capital). Furthermore, human-nature interactions in these cultural landscapes involve complex feedback loops, such as traditional knowledge of pastoralists and learning and inspiration. Traditional knowledge may be required to best utilise scarce natural resources in pastoral lands while at the same time, this knowledge is created and passed on informally by working in these landscapes. This makes it challenging to identify which NCP are derived for human benefits and which are feeding back into the maintenance of the landscape (Dean et al., 2021). The balance of environmental and social components created by adaptive human interventions (Guerra & Pinto-Correia, 2016) may imply that these pastoral systems are both constantly co-produced and co-producing.

The concept of co-production provides one of the various frameworks to zoom into these interactions and understand how humans derive the many benefits nature has to offer through their own contribution. In this literature review, we compiled evidence on how this is operationalised in empirical studies.

This literature review and the idea of co-production are conceptually based on the NCP framework of IPBES. We expect that with the increasing uptake of the NCP framework in research, more attention will be paid to the anthropogenic contributions to NCP. This will potentially close some of the knowledge gaps on NCP co-production.

4.1 | NCP and anthropogenic capital combinations

Our results provide evidence of co-production across all categories of NCP and anthropogenic capitals. Human capital was represented most frequently. Financial capital was mainly associated with material NCP and was otherwise mentioned in a minority of observations. This might be due to the difficulty in disentangling financial capital from other capital types. In fact, by definition, financial capital contributes to NCP by allowing its exchange for other types of capital, natural and anthropogenic. For example, financial capital is embedded in physical capital when building infrastructure or buying machines and other agricultural inputs. In turn, in exchange for money, one can become a member of an association and retrieve education or training. Therefore, we call for a cautious interpretation of these and other results, as observations on human, social, and physical capital might capture previous financial capital inputs, meaning that anthropogenic capital indicators might be embedded in each other.

As expected, we found more evidence on the co-production of material and non-material NCP than on regulating NCP. As hypothesised, material NCP were mostly associated with the input of physical capital related to infrastructure and built capital and, to a smaller extent, agricultural inputs. This result could partially be explained by the fact that most of the studies were conducted on a landscape scale, where infrastructure can play an important role. Furthermore, our results show that capitals are often combined, especially for material and regulating NCP. For example, physical capital is most frequently combined with social and human capital for co-producing material NCP.

For non-material NCP, our results support our hypothesis that co-production was predominantly associated with human and social capital. As we expected, physical capital, such as outdoor equipment, plays a minor role in the co-production of non-material NCP, although physical access to routes may be quite important to realise the actual use of non-material NCP (Crouzat et al., 2022).

We found less evidence for the co-production of regulating NCP. This could be because regulating NCP are only indirectly dependent on anthropogenic capitals, for example, when air purification is enhanced through the creation of urban green spaces (Jericó-Daminello et al., 2021). In general, some NCP are provided solely by natural capital or with only little anthropogenic contribution, such as water purification by riparian forests (Darwiche-Criado et al., 2017; Osborne & Kovacic, 1993). Other NCP are more dependent on anthropogenic inputs. Food production, for example, may not only rely on ecosystem functions such as soil formation but also farm labour, knowledge of farming techniques and machinery (Díaz et al., 2015). Furthermore, multiple anthropogenic capitals often come into play at the same time. For example, graziers may jointly develop knowledge through experimentation and practice of new wool and lamb production systems (Lavorel et al., 2020) or joint animal husbandry (Burton et al., 2008).

4.2 | Co-production in ecosystem management

The reviewed publications highlight the benefits of incorporating this knowledge in land management and decision-making (e.g. Torralba et al., 2018). Any attempt to achieve more sustainable landscape management needs to consider the factors underlying NCP co-production. This includes the biophysical characteristics of the land as well as the effects of management practices influenced by the socioeconomic context in which people live and operate (Garcia-Llorente et al., 2012; Henriksson Malinga et al., 2018).

Co-production of regulating NCP may be achieved through novel institutional arrangements such as Payment for Ecosystem Services Schemes (PES; Varela et al., 2018) or traditional multifunctional management schemes (Varela et al., 2020). These schemes may build on traditional ecological knowledge or indigenous knowledge that have been shown to create resilient landscapes (Congretel & Pinton, 2020; Kobluk et al., 2021).

For example, in the Mediterranean basin, wildfire control as a regulating NCP may be achieved through initiatives that incorporate livestock grazing for biomass removal. This involves social capital (institutional infrastructure, stakeholder communication), financial capital (transaction and compensation costs), physical capital (basic pastoral infrastructure), and natural capital (pasture land, livestock; Varela et al., 2018).

In addition to the role of humans in providing regulating NCP, especially psychological and spiritual connections of people with nature must be recognised in resource management (Russell et al., 2013).

In this literature review, most publications provide evidence at a single point in time. Planners, however, should consider the relationship between anthropogenic capital inputs and NCPs over time (Rieb et al., 2017). For instance, land-use planning may incorporate terraces or hedges as part of intercropping systems or landscape engineering to prevent long-term losses of soil organic carbon in the long-term (Weise et al., 2020). While drainage and fertilisers may initially generate high yields on agricultural fields, soil degradation could decrease yields in the long term (Rieb et al., 2017).

In addition, planners must consider the magnitude of anthropogenic capital inputs. When deciding about how to promote non-material NCP, planners may decide to aim for the benefit of a minimum amount of physical capital, such as roads and parking lots or tourist information spots, to facilitate the enjoyment of nature. Any addition of infrastructure can increase the benefit to people up to a tipping point upon which overdevelopment leads to crowded areas and degrades the natural experience (Rieb et al., 2017). However, the publications reviewed here do not provide evidence of these tipping points.

Similarly, it is still unknown how anthropogenic capital can substitute natural capital or NCP itself to provide NCP (Rieb et al., 2017). For example, flood risks can be reduced by increasing the height of dikes or by giving rivers more space to expand. Enhancing natural capital through the implementation of buffer stripes can reduce nutrient exports from agricultural land into the water cycle, and thus mimic this regulating NCP. In general, for successful management practices to mimic NCP it is important to note that without addressing the source of the problem, they may undermine the resilience of ecosystems in the long term and thus cause further loss of NCP (Lennox et al., 2022; Weise et al., 2020).

In addition, it is critical to unravel which NCP can be best co-produced with different forms of capital and actively promote synergies through management practices (Felipe-Lucia et al., 2018, 2022). Given the limited amount of evidence on synergies and trade-offs in NCP co-production, we can only confirm that interactions between different capitals in NCP provision are generally still overlooked in

NCP or ecosystem services research (Lee & Lautenbach, 2016). Future research should therefore make an effort to study (un)intended effects of co-production on other NCP, especially concerning the enhancement of provisioning NCP through different anthropogenic capital inputs, which seems to generate trade-offs more likely than synergies. The points mentioned above highlight that in order to manage multifunctional landscapes, we need to better understand the interactions of natural and anthropogenic capital in agricultural systems and how they can result in multiple NCP (Bennett et al., 2021).

4.3 | Limitations

With the aim to collate empirical evidence on NCP co-production in the research field of NCP and ecosystem services, we set a focus on empirical work in scientific journals, which may leave out potential additional evidence from the grey literature (e.g. Pérez-Soba Aguilar et al., 2019). Furthermore, we used Web of Science as the search engine, which could have potentially limited the number of publications retrieved for analysis. Combining results with those of other search engines, such as Scopus or Google Scholar, may be used for future reviews. Besides, restricting the search to publications in English may have ignored the non-English literature on co-production, which should be included in future studies.

In this literature review, we adhere to the IPBES framework that uses the concept of anthropogenic capitals and points to the role of humans in co-producing NCP. Consequently, with our search string, we aimed to find publications that incorporated the concepts of NCP co-production or anthropogenic capitals. However, this perspective may have limited the identification of studies that deal with co-production without incorporating this idea or explicitly referring to capitals or co-production, such as studies on nature-based solutions that potentially refer to the idea of co-production. For example, numerous studies set focus on human-nature interactions without pinpointing anthropogenic capital types (e.g. Chan et al., 2006, 2011; Paracchini et al., 2014). Although this idea is not defined as co-production in the literature, it adheres to the concept of co-production. Therefore, we may have missed relevant publications in this literature review. Nevertheless, with our small but evidence-based sample, we retrieved interesting insights into how the idea of co-production is implemented in current research. This review contributes to the understanding of NCP co-production concept and its operationalisation in real-world case studies. In this way, our paper provides a more complete picture of the emerging field of research.

4.4 | Challenges in co-production research

In the following, we summarise the main remaining challenges to fully incorporate the potential of the co-production concept in NCP research.

First, there is a lack of available data to measure anthropogenic contributions (Schröter et al., 2021). As a way forward, Balvanera (2022) compiled indicators and data sources for Essential Ecosystem Service Variable (EESV), including anthropogenic contributions, in their search for a global monitoring framework. For example, they suggest assessing anthropogenic contributions to crop pollination by monitoring the extent of planted bee habitats such as flower strips and hedgerows using remote sensing. Furthermore, they suggest measuring the anthropogenic contribution to wild food from marine fisheries by analysing the extent of physical infrastructure in terms of density of fishing boats with available global fishing effort data. To assess the infrastructure that supports physical and psychological experiences of wildlife viewing, high-resolution remote sensing is a potential source of data. These examples show that working with available data requires access to various databases on different spatial and consequently administrative scales. However, in case of the absence of existing data, compiling data on NCPs and anthropogenic capitals requires immense data collection efforts (Balvanera, 2022). In this review, evidence on NCP co-production was mainly found at the landscape scale and for single points in time. However, interactions between people and nature can occur at multiple spatial scales (Martín-López et al., 2019), and thus data on co-production should be collected and analysed across those. Similarly, with human-nature relationships varying over time (Rieb et al., 2017), analysis of co-production over larger time frames needs to be considered. An attempt to deal with these challenges would be the creation of large research platform studies such as the Biodiversity Exploratories in Germany (https://www.biodiversity-exploratories.de/en/). This special research platform permits scientists from different disciplines to collect and share data in real landscapes with a long-term perspective allowing the investigation of land-use intensity effects and biodiversity change at different spatial scales (Fischer et al., 2010).

Second, another challenge related to data collection is the fact that the interplay of natural and anthropogenic capitals can be seen as both a physical and a cognitive process. A physical process can be observed in agricultural intensification making use of irrigation, fertilisers, biocides, and mechanisation to manage existing lands more productively (Foley et al., 2011). A cognitive process occurs through different channels, such as knowing about an ecosystem, perceiving it, interacting directly with it, or living in it (Russell et al., 2013). These activities are strongly driven by knowledge, skills, preferences, and motivations (Bruley et al., 2021). These forms of co-production are often difficult to measure (e.g. sensory interaction with an ecosystem when smelling nearby pine trees) and receive less attention in ecosystem services and NCP research (Russell et al., 2013).

For example, traditional social-ecological systems are effective in preserving regulating NCP such as flood or fire prevention to maintain resilient landscapes. These systems are shaped by natural and human factors, such as learning through experience, local knowledge, and the ability to self-organise. Although, as such, traditional social-ecological systems are an example of NCP co-production, the role of anthropogenic factors is under researched (Gardner & Dekens, 2007). This may not only be part of the knowledge gap on NCP co-production but also underestimated when making a decision in land-use management.

Often, co-production is a mixture of both physical and cognitive processes. For example, the appreciation of nature's beauty may not only be the result of cognitive or psychological processes inherent in individuals, but also of physical management practices, such as tourism infrastructure (Crouzat et al., 2022; Palomo et al., 2016). Choosing and combining data collection methods that can capture information for both physical and cognitive processes remains a challenge that still needs to be addressed. Especially, cognitive processes include the feedback loop from NCP to anthropogenic capitals, for instance, when spending time in nature as a non-material NCP leads to attention restoration and positively affects human cognition and health (human capital) (Marselle et al., 2021). This is an important link that needs to be considered in the study design when investigating NCP co-production.

Third, a major constraint in detecting evidence on NCP co-production is the suitability of analytic methods. A large share of the evidence we presented comes from content analyses or analysis of variance. These methods can provide information on the role of anthropogenic capitals, but they have limited explanatory power of the causal relationships between capital types and NCP. To increase the strength of evidence for NCP co-production, we propose to study causal inference through path analyses. Based on structural equation modelling, for instance, it is possible to disentangle the types of relationship between anthropogenic capitals and their response effect on NCP (Grace, 2006; Lefcheck, 2016; Stenegren et al., 2017).

Fourth, models and tools to analyse NCP most often assume that anthropogenic capital inputs are implied (e.g. modelling timber production only includes measurement of trees and assumes that infrastructure and management are in place) or ignored (e.g. modelling pollination neglects the contribution of managed honeybees), which hinder targeted analyses of these inputs. On the one hand, we require integrated models that allow us to incorporate biophysical and anthropogenic factors together with multiple NCP to capture the effect of co-production on synergies and trade-offs. On the other hand, adding complexity to NCP models will come at a cost, such as difficulties in model testing or their application by end users (Rieb et al., 2017). Therefore, a compromise needs to be found with greater explicit analytical approaches to assess the co-production of NCP.

Fifth, in parts of the world, it may be difficult to distinguish between the natural and human input into co-production as the cultural context regards the two as one (Russell et al., 2013), for instance, when people and nature are connected through spiritual and cosmological processes (Hill et al., 2021). This highlights the need for participatory and situated research approaches (Chan & Satterfield, 2020; Fish et al., 2016) that respect the local definitions of nature (Keune et al., 2022).

4.5 | Future research directions

Based on the results of this literature review and the discussion above, we identify three main research paths that will contribute to advance understanding of NCP co-production.

1. *Typology and mechanisms of relationships between anthropogenic capitals and NCP*: A better understanding of the mechanisms behind the relationships between different anthropogenic capitals and NCP and their interactions over space and time is needed, to inform sustainable land management to foster both biodiversity and sustainable NCP provision. Furthermore, we need to understand the feedback loops between NCP, and natural and anthropogenic capitals (Palomo et al., 2016) to assess the resilience of co-produced systems.

Importantly, the degree of reversibility of anthropogenic capital inputs and potential hysteresis effects need to be understood, i.e., whether an initial ecosystem state is recovered after anthropogenic capital inputs and how nonlinear change may occur in ecosystems and NCP provision due to different capital inputs.

2. *Substitutability of natural capital by anthropogenic capital*: Investigating to what extent natural contributions can be replaced by anthropogenic contributions is key to address current discussions on sustainability. The assumption of substitutability of natural and anthropogenic capital could lead to acceptance of the decrease or degradation of certain capital types. However, if substitutability is not given, this would imply the need for maintenance of all capital types (Schröter et al., 2021).
3. *Governance of NCP co-production*: In addition to the supply and interrelatedness of different capitals, governance of social-ecological systems and their anthropogenic and natural capitals plays an important role in the co-production of NCP (Isaac et al., 2022). Identifying which stakeholders and governance arrangements affect the allocation of capitals and NCP can therefore contribute to designing policies that ensure more sustainable and equitable co-production, delivery, and use of NCP.

5 | CONCLUSIONS

The analysis of NCP co-production can render important insights into the relationships of natural and anthropogenic capitals and thereby the sustained provision of NCP into the future. As a result of this review, however, field studies have only marginally operationalised the concept of NCP co-production so far. Those publications explicitly incorporating the concept in their research highlight the benefits for planners who need to address the complexities of social-ecological systems of landscapes. The evidence of co-production mainly stems from content analysis or analysis of variance. Observations on the co-production of material and regulating NCP involve physical and human capital most frequently. Observations on the co-production of non-material NCP involve most frequently social and human capital. Evidence gaps persist on the mechanisms and shapes of relationships between capitals and NCP. Future studies should explore and apply data and methodologies that can provide stronger evidence on NCP co-production. This will not only enhance the emerging research field of NCP co-production but also contribute to sustainable ecosystem management.

AUTHOR CONTRIBUTIONS

Jana Kachler and Roman Isaac reviewed the literature and coded the articles; Jana Kachler performed the analysis and prepared the figures. Jana Kachler led the writing of the manuscript. All authors critically contributed to the drafts and gave their final approval for publication.

ACKNOWLEDGEMENTS

This work is funded by DFG Priority Program 1374 "Biodiversity Exploratories" (433163377). It is also supported by iDiv funded by the German Research Foundation (DFG-FZT 118, 202548816). Open access funding enabled and organized by ProjektDEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. Aletta Bonn is Associate Editor of People and Nature, but was not involved in the peer review and decision-making processes for this article.

DATA AVAILABILITY STATEMENT

Data are available on Zenodo at https://doi.org/10.5281/zenodo.7908413.

ORCID

Jana Kachler https://orcid.org/0000-0003-0536-2820
Roman Isaac https://orcid.org/0000-0002-0007-7433
Berta Martín-López https://orcid.org/0000-0003-2622-0135
Aletta Bonn https://orcid.org/0000-0002-8345-4600
María R. Felipe-Lucia https://orcid.org/0000-0003-1915-8169

REFERENCES

Auer, A., Maceira, N., & Nahuelhual, L. (2017). Agriculturisation and trade-offs between commodity production and cultural ecosystem services: A case study in Balcarce County. *Journal of Rural Studies*, *53*, 88–101. https://doi.org/10.1016/j.jrurstud.2017.05.013

Balvanera, P. (2022). Essential ecosystem service variables for monitoring progress towards sustainability. *Current Opinion in Environmental Sustainability*, *9*, 101152.

Bennett, E. M., Baird, J., Baulch, H., Chaplin-Kramer, R., Fraser, E., Loring, P., Morrison, P., Parrott, L., Sherren, K., Winkler, K. J., Cimon-Morin, J., Fortin, M.-J., Kurylyk, B. L., Lundholm, J., Poulin, M., Rieb, J. T., Gonzalez, A., Hickey, G. M., Humphries, M., … Lapen, D. (2021). Ecosystem services and the resilience of agricultural landscapes. *Advances in Ecological Research*, *64*, 1–43. https://doi.org/10.1016/bs.aecr.2021.01.001

Bhattacharjee, A., Sadadev, B. M., Karmacharya, D. K., Baral, R., Pérez-García, J. M., Giménez Casalduero, A., Sánchez-Zapata, J. A., & Anadón, J. D. (2022). Local ecological knowledge and education drive farmers' contrasting perceptions of scavengers and their function in Nepal. *People and Nature*, *4*(3), 786–803. https://doi.org/10.1002/pan3.10315

Bianchi, F. J. J. A., Mikos, V., Brussaard, L., Delbaere, B., & Pulleman, M. M. (2013). Opportunities and limitations for functional agrobiodiversity in the European context. *Environmental Science & Policy*, *27*, 223–231. https://doi.org/10.1016/j.envsci.2012.12.014

Bravo-Monroy, L., Tzanopoulos, J., & Potts, S. G. (2015). Ecological and social drivers of coffee pollination in Santander, Colombia. *Agriculture Ecosystems & Environment*, *211*, 145–154. https://doi.org/10.1016/j.agee.2015.06.007

Bruley, E., Locatelli, B., & Lavorel, S. (2021). Nature's contributions to people: Coproducing quality of life from multifunctional landscapes. *Ecology and Society*, *26*(1), art12. https://doi.org/10.5751/ES-12031-260112

Burton, R. J. F., Schwarz, G., Brown, K. M., & Ian, T. (2008). The future of public goods provision in upland regions: Learning from hefted commons in the Lake District, UK. In *Drivers of environmental change in uplands* (pp. 337–350). Routledge.

Chan, K. M. A., Guerry, A. D., Balvanera, P., Klain, S., Satterfield, T., Basurto, X., Bostrom, A., Chuenpagdee, R., Gould, R., Halpern, B. S., Hannahs, N., Levine, J., Norton, B., Ruckelshaus, M., Russell, R., Tam, J., & Woodside, U. (2012). Where are cultural and social in ecosystem services? A framework for constructive engagement. *BioScience*, *62*(8), 744–756. https://doi.org/10.1525/bio.2012.62.8.7

Chan, K. M. A., Hoshizaki, L., & Klinkenberg, B. (2011). Ecosystem services in conservation planning: Targeted benefits vs. co-benefits or costs? *PLoS ONE*, *6*(9), e24378. https://doi.org/10.1371/journal.pone.0024378

Chan, K. M. A., & Satterfield, T. (2020). The maturation of ecosystem services: Social and policy research expands, but whither biophysically informed valuation? *People and Nature*, *2*(4), 1021–1060. https://doi.org/10.1002/pan3.10137

Chan, K. M. A., Satterfield, T., & Goldstein, J. (2012). Rethinking ecosystem services to better address and navigate cultural values. *Ecological Economics*, *74*, 8–18. https://doi.org/10.1016/j.ecolecon.2011.11.011

Chan, K. M. A., Shaw, M. R., Cameron, D. R., Underwood, E. C., & Daily, G. C. (2006). Conservation planning for ecosystem services. *PLoS Biology*, *4*(11), e379. https://doi.org/10.1371/journal.pbio.0040379

Congretel, M., & Pinton, F. (2020). Local knowledge, know-how and knowledge mobilized in a globalized world: A new approach of indigenous local ecological knowledge. *People and Nature*, *2*(3), 527–543. https://doi.org/10.1002/pan3.10142

Cook, D., Davíðsdóttir, B., & Malinauskaite, L. (2020). A cascade model and initial exploration of co-production processes underpinning the ecosystem services of geothermal areas. *Renewable Energy*, *161*, 917–927. https://doi.org/10.1016/j.renene.2020.07.155

Crouzat, E., De Frutos, A., Grescho, V., Carver, S., Büermann, A., Carvalho-Santos, C., Kraemer, R., Mayor, S., Pöpperl, F., Rossi, C., Schröter, M., Stritih, A., Sofia Vaz, A., Watzema, J., & Bonn, A. (2022). Potential supply and actual use of cultural ecosystem services in mountain protected areas and their surroundings. *Ecosystem Services*, *53*, 101395. https://doi.org/10.1016/j.ecoser.2021.101395

Darwiche-Criado, N., Comín, F. A., Masip, A., García, M., Eismann, S. G., & Sorando, R. (2017). Effects of wetland restoration on nitrate removal in an irrigated agricultural area: The role of in-stream and off-stream wetlands. *Wetlands and Buffer Zones in Watershed Management*, *103*, 426–435. https://doi.org/10.1016/j.ecoleng.2016.03.016

Dean, G., Rivera-Ferre, M. G., Rosas-Casals, M., & Lopez-i-Gelats, F. (2021). Nature's contribution to people as a framework for examining socioecological systems: The case of pastoral systems. *Ecosystem Services*, *49*, 101265. https://doi.org/10.1016/j.ecoser.2021.101265

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J. R., Arico, S., Báldi, A., Bartuska, A., Baste, I. A., Bilgin, A., Brondizio, E., Chan, K. M., Figueroa, V. E., Duraiappah, A., Fischer, M., Hill, R., … Zlatanova, D. (2015). The IPBES conceptual framework—Connecting nature and people. *Current Opinion in Environmental Sustainability*, *14*, 1–16. https://doi.org/10.1016/j.cosust.2014.11.002

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., … Shirayama, Y. (2018). Assessing nature's contributions to people. *Science*, *359*, 270–272. https://doi.org/10.1126/science.aap8826

Dvarskas, A. (2018). Mapping ecosystem services supply chains for coastal Long Island communities: Implications for resilience planning. *Ecosystem Services*, *30*(A), 14–26. https://doi.org/10.1016/j.ecoser.2018.01.008

Fischer, A., & Eastwood, A. (2016). Coproduction of ecosystem services as human-nature interactions-an analytical framework. *Land Use Policy*, *52*, 41–50. https://doi.org/10.1016/j.landusepol.2015.12.004

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., Renner, S., Schöning, I., Schumacher, U., Wells, K., Buscot, F., Kalko, E. K. V., Linsenmair, K. E., Schulze, E.-D., & Weisser, W. W. (2010). Implementing large-scale and long-term functional biodiversity research: The biodiversity Exploratories. *Basic and Applied Ecology*, *11*(6), 473–485. https://doi.org/10.1016/j.baae.2010.07.009

Fish, R., Church, A., Willis, C., Winter, M., Tratalos, J. A., Haines-Young, R., & Potschin, M. (2016). Making space for cultural ecosystem services: Insights from a study of the UK nature improvement initiative. *Shared, Plural and Cultural Values*, *21*, 329–343. https://doi.org/10.1016/j.ecoser.2016.09.017

Felipe-Lucia, M. R., Comín, F. A., & Bennett, E. M. (2014). Interactions among ecosystem services across land uses in a floodplain agroecosystem. *Ecology and Society*, *19*(1). https://doi.org/10.5751/es-06249-190120

Felipe-Lucia, M. R., Guerrero, A. M., Alexander, S. M., Ashander, J., Baggio, J. A., Barnes, M. L., Bodin, Ö., Bonn, A., Fortin, M.-J., Friedman, R. S., Gephart, J. A., Helmstedt, K. J., Keyes, A. A., Kroetz, K., Massol, F., Pocock, M. J. O., Sayles, J., Thompson, R. M., Wood, S. A., & Dee, L. E. (2022). Conceptualizing ecosystem services using social–ecological networks. *Trends in Ecology & Evolution*, *37*(3), 211–222. https://doi.org/10.1016/j.tree.2021.11.012

Felipe-Lucia, M. R., Soliveres, S., Penone, C., Manning, P., van der Plas, F., Boch, S., Prati, D., Ammer, C., Schall, P., Gossner, M. M., Bauhus, J., Buscot, F., Blaser, S., Blüthgen, N., de Frutos, A., Ehbrecht, M., Frank, K., Goldmann, K., Hänsel, F., … Allan, E. (2018). Multiple forest attributes underpin the supply of multiple ecosystem services. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-07082-4

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337–342. https://doi.org/10.1038/nature10452

Garcia-Llorente, M., Martin-Lopez, B., Iniesta-Arandia, I., Lopez-Santiago, C. A., Aguilera, P. A., & Montes, C. (2012). The role of multi-functionality in social preferences toward semi-arid rural landscapes: An ecosystem service approach. *Environmental Science & Policy*, *19–20*, 136–146. https://doi.org/10.1016/j.envsci.2012.01.006

Gardner, J. S., & Dekens, J. (2007). Mountain hazards and the resilience of social–ecological systems: Lessons learned in India and Canada. *Natural Hazards*, *41*(2), 317–336. https://doi.org/10.1007/s11069-006-9038-5

Goodwin, N. R. (2003). *Five Kinds of Capital: Useful Concepts for Sustainable Development*. 03, 14 https://doi.org/10.22004/AG.ECON.15595

Grace, J. (2006). *Structural equation modeling and natural systems*. Cambridge University Press.

Guerra, C. A., & Pinto-Correia, T. (2016). Linking farm management and ecosystem service provision: Challenges and opportunities for soil erosion prevention in Mediterranean Silvo-pastoral systems. *Land Use Policy*, *51*, 54–65. https://doi.org/10.1016/j.landusepol.2015.10.028

Henriksson Malinga, R., Jewitt, G. P. W., Lindborg, R., Andersson, E., & Gordon, L. J. (2018). On the other side of the ditch: Exploring contrasting ecosystem service coproduction between smallholder and commercial agriculture. *Ecology and Society*, *23*(4), art9. https://doi.org/10.5751/ES-10380-230409

Hicks, C. C., & Cinner, J. E. (2014). Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(50), 17791–17796. https://doi.org/10.1073/pnas.1413473111

Hill, R., Díaz, S., Pascual, U., Stenseke, M., Molnár, Z., & Van Velden, J. (2021). Nature's contributions to people: Weaving plural perspectives. *One Earth*, *4*(7), 910–915. https://doi.org/10.1016/j.oneear.2021.06.009

Hipólito, J., Viana, B. F., & Garibaldi, L. A. (2016). The value of pollinator–friendly practices: Synergies between natural and anthropogenic assets. *Basic and Applied Ecology*, *17*(8), 659–667. https://doi.org/10.1016/j.baae.2016.09.003

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*, 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

Isaac, R., Kachler, J., Winkler, K. J., Albrecht, E., Felipe-Lucia, M. R., & Martín-López, B. (2022). Chapter ten—Governance to manage the complexity of nature's contributions to people co-production. In J. M. Holzer, J. Baird, & G. M. Hickey (Eds.), *Advances in ecological research* (Vol. *66*, pp. 293–321). Academic Press. https://doi.org/10.1016/bs.aecr.2022.04.009

Jackson, L. E., Pulleman, M. M., Brussaard, L., Bawa, K. S., Brown, G. G., Cardoso, I. M., de Ruiter, P. C., Garcia-Barrios, L., Hollander, A. D., Lavelle, P., Ouedraogo, E., Pascual, U., Setty, S., Smukler, S. M., Tscharntke, T., & Van Noordwijk, M. (2012). Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. *Global Environmental Change-Human and Policy Dimension*, *22*(3), 623–639. https://doi.org/10.1016/j.gloenvcha.2012.05.002

Jericó-Daminello, C., Schröter, B., Mancilla Garcia, M., & Albert, C. (2021). Exploring perceptions of stakeholder roles in ecosystem services coproduction. *Ecosystem Services*, *51*, 101353. https://doi.org/10.1016/j.ecoser.2021.101353

Kadykalo, A. N., López-Rodriguez, M. D., Ainscough, J., Droste, N., Ryu, H., Ávila-Flores, G., Le Clec'h, S., Muñoz, M. C., Nilsson, L., Rana, S., Sarkar, P., Sevecke, K. J., & Harmáčková, Z. V. (2019). Disentangling 'ecosystem services' and 'nature's contributions to people'. *Ecosystems and People*, *15*(1), 269–287. https://doi.org/10.1080/26395916.2019.1669713

Keune, H., Immovilli, M., Keller, R., Maynard, S., McElwee, P., Molnár, Z., Olsson, G. A., Payyappallimana, U., Schneiders, A., Schoolenberg, M., Subramanian, S. M., & Reeth, W. V. (2022). Defining nature. In I. J. Visseren-Hamakers & M. T. J. Kok (Eds.), *Transforming biodiversity governance* (1st ed., pp. 25–42). Cambridge University Press. https://doi.org/10.1017/9781108856348.003

Kobluk, H. M., Gladstone, K., Reid, M., Brown, K., Krumhansl, K. A., & Salomon, A. K. (2021). Indigenous knowledge of key ecological processes confers resilience to a small-scale kelp fishery. *People and Nature*, *3*(3), 723–739. https://doi.org/10.1002/pan3.10211

Lavelle, P., Doledec, S., de Sartre, X. A., Decaens, T., Gond, V., Grimaldi, M., Oszwald, J., Hubert, B., Ramirez, B., Veiga, I., de Souza, S., de

Assis, W. S., Michelotti, F., Martins, M., Feijoo, A., Bommel, P., Castaneda, E., Chacon, P., Desjardins, T., … Velasquez, J. (2016). Unsustainable landscapes of deforested Amazonia: An analysis of the relationships among landscapes and the social, economic and environmental profiles of farms at different ages following deforestation. *Global Environmental Change-Human and Policy Dimensions*, *40*, 137–155. https://doi.org/10.1016/j.gloenvcha.2016.04.009

Lavorel, S., Locatelli, B., Colloff, M. J., & Bruley, E. (2020). Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190119. https://doi.org/10.1098/rstb.2019.0119

Lee, H., & Lautenbach, S. (2016). A quantitative review of relationships between ecosystem services. *Ecological Indicators*, *66*, 340–351. https://doi.org/10.1016/j.ecolind.2016.02.004

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*(5), 573–579. https://doi.org/10.1111/2041-210X.12512

Lennox, R. J., Brownscombe, J. W., Darimont, C., Horodysky, A., Levi, T., Raby, G. D., & Cooke, S. J. (2022). The roles of humans and apex predators in sustaining ecosystem structure and function: Contrast, complementarity and coexistence. *People and Nature.*, *4*, 1071–1082. https://doi.org/10.1002/pan3.10385

Marselle, M. R., Hartig, T., Cox, D. T., De Bell, S., Knapp, S., Lindley, S., Triguero-Mas, M., Böhning-Gaese, K., Braubach, M., Cook, P. A., de Vries, S., Heintz-Buschart, A., Hofmann, M., Irvine, K. N., Kabisch, N., Kolek, F., Kraemer, R., Markevych, I., Martens, D., … Bonn, A. (2021). Pathways linking biodiversity to human health: A conceptual framework. *Environment International*, *150*, 106420. https://doi.org/10.1016/j.envint.2021.106420

Martín-López, B., Felipe-Lucia, M. R., Bennett, E. M., Norström, A., Peterson, G., Plieninger, T., Hicks, C. C., Turkelboom, F., García-Llorente, M., Jacobs, S., Lavorel, S., & Locatelli, B. (2019). A novel telecoupling framework to assess social relations across spatial scales for ecosystem services research. *Journal of Environmental Management*, *241*, 251–263. https://doi.org/10.1016/j.jenvman.2019.04.029

Millennium Ecosystem Assessment (Ed.). (2005). *Ecosystems and human well-being: Synthesis*. Island Press.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses. *The PRISMA Statement*, *6*(7). https://doi.org/10.1371/journal.pmed.1000097

Mouchet, M. A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., & Lavorel, S. (2014). An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Global Environmental Change*, *28*, 298–308. https://doi.org/10.1016/j.gloenvcha.2014.07.012

Osborne, L., & Kovacic, D. (1993). Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology*, *29*(2), 243–258. https://doi.org/10.1111/j.1365-2427.1993.tb00761.x

Ostrom, E. (1996). Crossing the great divide: Coproduction, synergy, and development. *World Development*, *24*(6), 1073–1087. https://doi.org/10.1016/0305-750X(96)00023-X

Palliwoda, J., Fischer, J., Felipe-Lucia, M. R., Palomo, I., Neugarten, R., Büermann, A., Price, M. F., Torralba, M., Eigenbrod, F., Mitchell, M. G. E., Beckmann, M., Seppelt, R., & Schröter, M. (2021). Ecosystem service coproduction across the zones of biosphere reserves in Europe. *Ecosystems and People*, *17*(1), 491–506. https://doi.org/10.1080/26395916.2021.1968501

Palomo, I., Felipe-Lucia, M. R., Bennett, E. M., Martín-López, B., & Pascual, U. (2016). Disentangling the pathways and effects of ecosystem service co-production. *Advances in Ecological Research*, *54*, 245–283. https://doi.org/10.1016/bs.aecr.2015.09.003

Paracchini, M. L., Zulian, G., Kopperoinen, L., Maes, J., Schägner, J. P., Termansen, M., Zandersen, M., Perez-Soba, M., Scholefield, P. A., & Bidoglio, G. (2014). Mapping cultural ecosystem services: A framework to assess the potential for outdoor recreation across the EU. *Ecological Indicators*, *45*, 371–385. https://doi.org/10.1016/j.ecolind.2014.04.018

Pérez-Soba Aguilar, M., Elbersen, B., Braat, L., Kempen, M., Van Der Wijngaart, R., Staritsky, I., Rega, C., & Paracchini, M. (2019). *The emergy perspective: Natural and anthropic energy flows in agricultural biomass production*. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/526985

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, *114*(8), 1571–1596. https://doi.org/10.1093/aob/mcu205

Rieb, J. T., Chaplin-Kramer, R., Daily, G. C., Armsworth, P. R., Böhning-Gaese, K., Bonn, A., Cumming, G. S., Eigenbrod, F., Grimm, V., Jackson, B. M., Marques, A., Pattanayak, S. K., Pereira, H. M., Peterson, G. D., Ricketts, T. H., Robinson, B. E., Schröter, M., Schulte, L. A., Seppelt, R., … Bennett, E. M. (2017). When, where, and how nature matters for ecosystem services: Challenges for the next generation of ecosystem service models. *Bioscience*, *67*(9), 820–833. https://doi.org/10.1093/biosci/bix075

Russell, R., Guerry, A. D., Balvanera, P., Gould, R. K., Basurto, X., Chan, K. M. A., Klain, S., Levine, J., & Tam, J. (2013). Humans and nature: How knowing and experiencing nature affect well-being. *Annual Review of Environment and Resources*, *38*(1), 473–502. https://doi.org/10.1146/annurev-environ-012312-110838

Schröter, M., Egli, L., Brüning, L., & Seppelt, R. (2021). Distinguishing anthropogenic and natural contributions to coproduction of national crop yields globally. *Scientific Reports*, *11*(1), 10821. https://doi.org/10.1038/s41598-021-90340-1

Setten, G., & Brown, K. M. (2018). Ecosystem services as an integrative framework: What is the potential? *Land Use Policy*, *75*, 549–556. https://doi.org/10.1016/j.landusepol.2018.04.023

Silk, M., Correia, R., Veríssimo, D., Verma, A., & Crowley, S. L. (2021). The implications of digital visual media for human–nature relationships. *People and Nature*, *3*(6), 1130–1137. https://doi.org/10.1002/pan3.10284

Spangenberg, J. H., Görg, C., Truong, D. T., Tekken, V., Bustamante, J. V., & Settele, J. (2014). Provision of ecosystem services is determined by human agency, not ecosystem functions. Four case studies. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *10*(1), 40–53. https://doi.org/10.1080/21513732.2014.884166

Stenegren, M., Berg, C., Padilla, C. C., David, S.-S., Montoya, J. P., Yager, P. L., & Foster, R. A. (2017). Piecewise structural equation model (SEM) disentangles the environmental conditions favoring diatom diazotroph associations (DDAs) in the Western Tropical North Atlantic (WTNA). *Frontiers in Microbiology*, *8*, 810. https://doi.org/10.3389/fmicb.2017.00810

Torralba, M., Oteros-Rozas, E., Moreno, G., & Plieninger, T. (2018). Exploring the role of management in the coproduction of ecosystem services from Spanish wooded rangelands. *Rangeland Ecology & Management*, *71*(5), 549–559. https://doi.org/10.1016/j.rama.2017.09.001

Varela, E., Górriz-Mifsud, E., Ruiz-Mirazo, J., & López-i-Gelats, F. (2018). Payment for targeted grazing: Integrating local shepherds into wildfire prevention. *Forests*, *9*(8), 464.

Varela, E., Pulido, F., Moreno, G., & Zavala, M. Á. (2020). 'Targeted policy proposals for managing spontaneous forest expansion in the Mediterranean' ed. Josep Espelta. *Journal of Applied Ecology*, *57*(12), 2373–2380. https://doi.org/10.3390/f9080464

Vialatte, A., Barnaud, C., Blanco, J., Ouin, A., Choisis, J.-P., Andrieu, E., Sheeren, D., Ladet, S., Deconchat, M., Clement, F., Esquerre, D., & Sirami, C. (2019). A conceptual framework for the governance of multiple ecosystem services in agricultural landscapes. *Landscape Ecology*, *34*(7, SI), 1653–1673. https://doi.org/10.1007/s10980-019-00829-4

Weise, H., Auge, H., Baessler, C., Bärlund, I., Bennett, E. M., Berger, U., Bohn, F., Bonn, A., Borchardt, D., Brand, F., Chatzinotas, A., Corstanje, R., De Laender, F., Dietrich, P., Dunker, S., Durka, W., Fazey, I., Groeneveld, J., Guilbaud, C. S. E., … Grimm, V. (2020). Resilience trinity: Safeguarding ecosystem functioning and services across three different time horizons and decision contexts. *Oikos*, *129*(4), 445–456. https://doi.org/10.1111/oik.07213

Zeweld, W., Van Huylenbroeck, G., Tesfay, G., Azadi, H., & Speelman, S. (2020). Sustainable agricultural practices, environmental risk mitigation and livelihood improvements: Empirical evidence from Northern Ethiopia. *Land Use Policy*, *95*, 103799. https://doi.org/10.1016/j.landusepol.2019.01.002

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Additional information on indicators and their description for the coding process.

Table S2. Additional information on applied definitions of NCP supply, demand, and distribution.

Figure S1. Prisma flow chart depicting the literature screening process. Adapted from: PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Flow Diagram. Protocol applied for this literature review for identifying publications employing anthropogenic capital indicators to investigate the generation of NCP. Source: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. https://doi.org/10.1371/journal.pmed.1000097.

Figure S2. (a) Number of publications per temporal scale. (b) Number of publications per spatial scale.

Figure S3. Number of publications that use primary data, secondary data, or data from both sources.

Figure S4. Share of publications per perspective on NCP and type of data.

How to cite this article: Kachler, J., Isaac, R., Martín-López, B., Bonn, A., & Felipe-Lucia, M. R. (2023). Co-production of nature's contributions to people: What evidence is out there? *People and Nature*, *5*, 1119–1134. https://doi.org/10.1002/pan3.10493