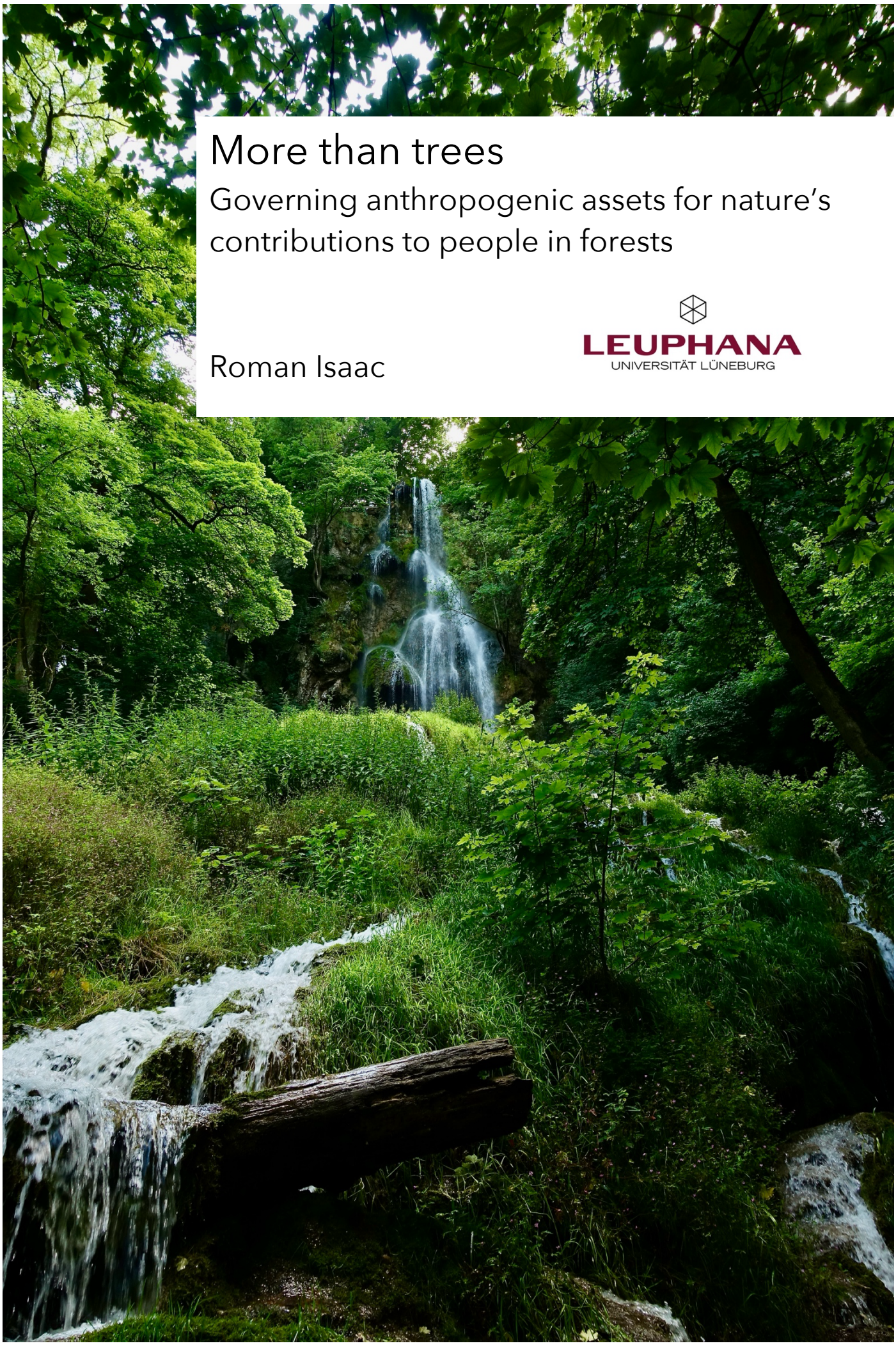

More than trees

Governing anthropogenic assets for nature's contributions to people in forests

Roman Isaac

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More than trees

Governing anthropogenic assets for nature's contributions to people in forests

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And into the forest I go, to lose my mind and find my soul.

John Muir

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Finally, I want to express my gratitude to my partner Annika for her moral support during this PhD journey, for sharing adventures with me, and for always having my back throughout the last decade.

Abstract

Forests are multifunctional and provide multiple material, regulating, and non-material nature's contributions to people (NCP), such as timber, carbon storage, or recreation potential. Research has long regarded NCP as a "free gift" from nature. In fact, NCP in forests and other ecosystems are influenced by human agency and co-produced in an interplay of natural and anthropogenic assets, also known as capitals. Human capital refers to people's abilities in the form of knowledge, skills, or manual labour. Social capital includes human-human interactions in networks or institutions. Physical capital refers to all machinery or infrastructure used to co-produce NCP. Financial encompasses all monetary flows used to trade, maintain, or enhance other anthropogenic and natural capitals. Forests, their contributions to people, and the anthropogenic capitals co-producing these are governed by various actors across multiple governance levels and through different governance modes. Governance can be hierarchical, based on scientific evidence, collaborative, or based on incentives. The graphical abstract on the following page illustrates how governance on various levels affects the interplay of anthropogenic and natural capitals to co-produce NCP.

Despite an increasing body of literature on NCP co-production, the effects of governance on the interplay of anthropogenic and natural capitals in their provision still need to be discovered. This dissertation seeks to fill this gap by approaching the topic from three perspectives: research, policy, and practice. This dissertation consists of five chapters. Chapter I provides a theoretical framework for this dissertation by outlining how the following chapters (II-V) contribute to these three perspectives. The research perspective examines how the scientific literature has studied the governance of NCP co-production across ecosystems (Chapter II) and explores conceptual, research practice-related, and thematic challenges for future research (Chapter V). The policy and practice perspectives focus on three case study sites to investigate how NCP co-production in forests is governed. Chapter III employs a policy document analysis to examine how policy at different governance levels intends to govern anthropogenic capitals for the co-production of forest NCP. Chapter IV uses social network analysis based on forest actor interviews to understand which actors are most relevant in managing different anthropogenic capitals in the co-production of forest NCP.

The findings of this dissertation indicate that three themes of governing anthropogenic capitals in NCP co-production exist. First, financial capital flows strongly influence decision-making processes on using anthropogenic capitals to co-produce material NCP. Second, regulating NCP are co-produced by various actors and governed collaboratively. Third, protected areas govern the co-production of non-material NCP by conserving natural spaces and managing the infrastructure necessary to access them. These findings hold implications for research, policy, and practice. Research needs to understand better how multiple values of nature affect the choice of anthropogenic capitals and identify how governance can foster sustainable forms of NCP co-production. To achieve sustainable co-production, policymakers need to determine how policy can minimise trade-offs between NCP and anthropogenic capitals. Practitioners can use these findings to argue for support that decreases their financial dependence on material NCP and recognises their work for regulating and non-material NCP.

Graphical Abstract

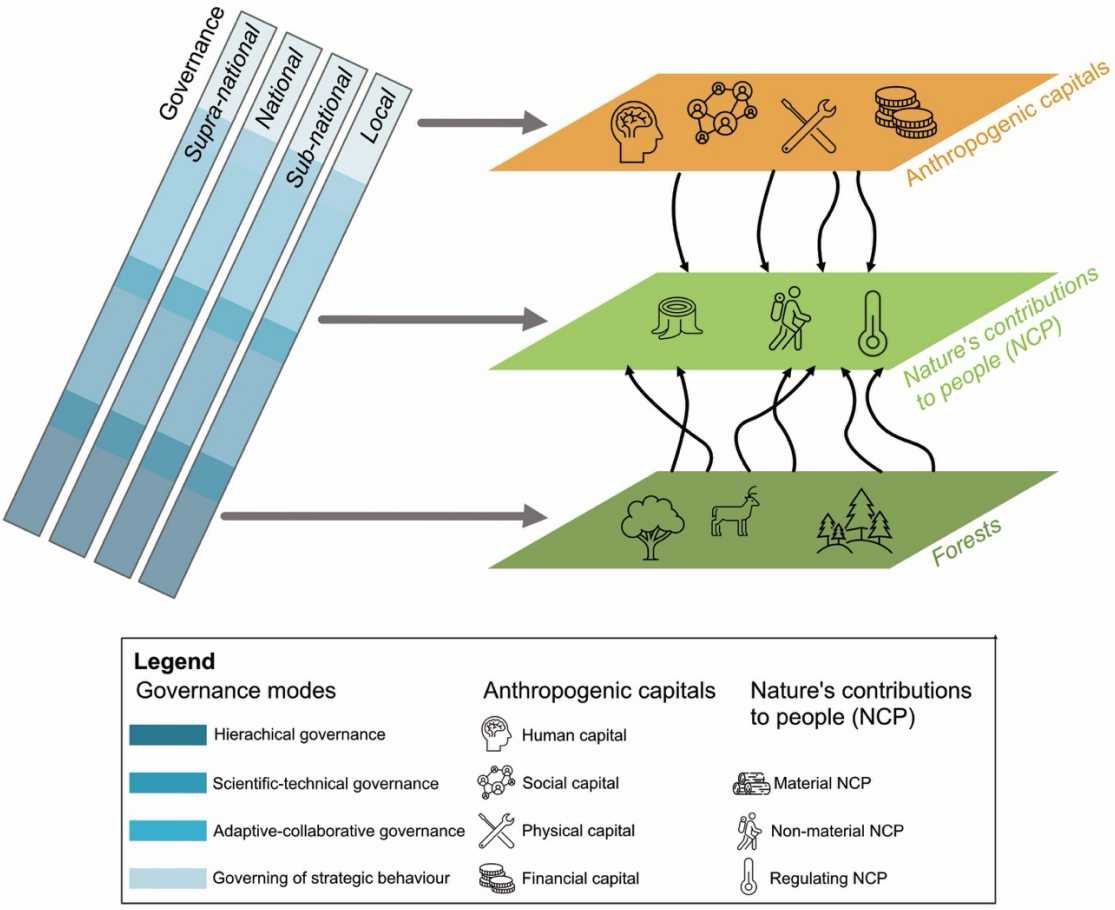


Figure: Governing the co-production of nature's contributions to people. Governance levels from the local to the supra-national affect the interplay of forests and anthropogenic capitals in the co-production of nature's contributions to people by using four intersecting governance modes, i.e., hierarchical, scientific-technical, and adaptive-collaborative governance, as well as the governing of strategic behaviour (Primmer et al., 2015). Figure adapted from Isaac et al. (2023).

Zusammenfassung

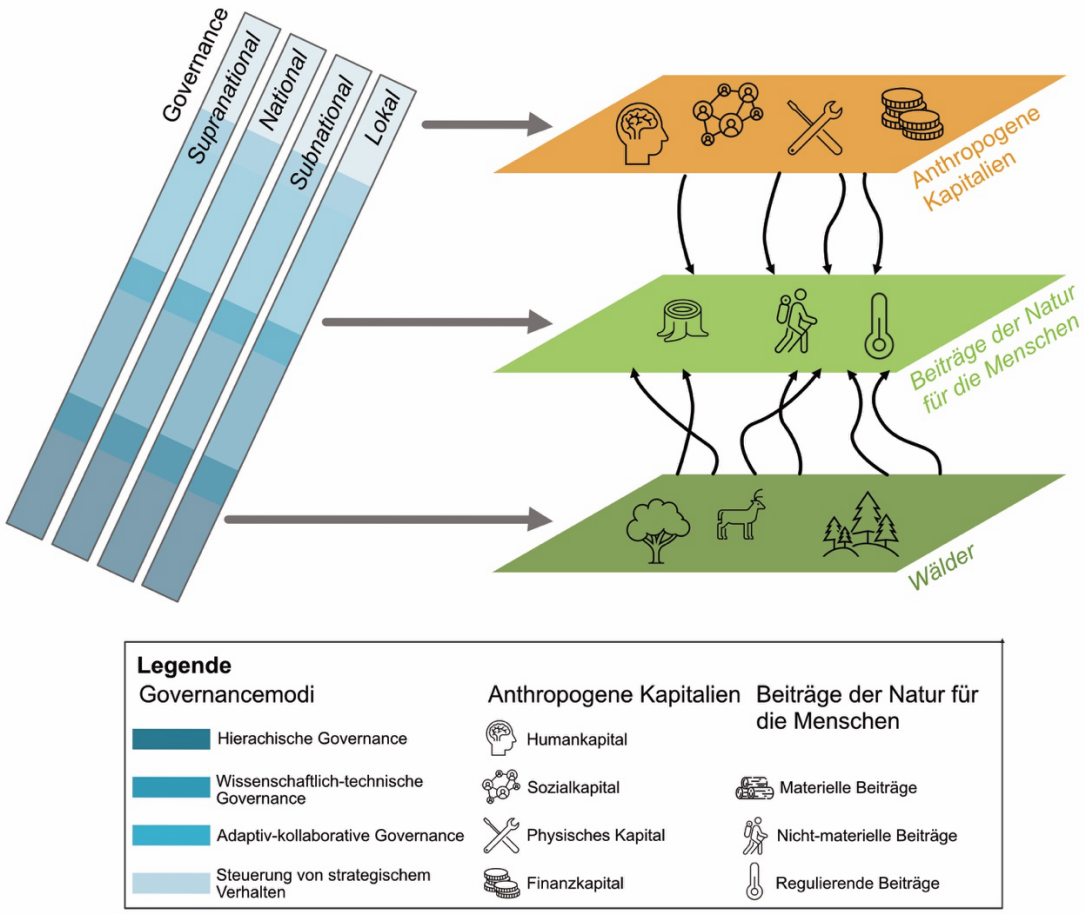
Wälder sind multifunktional und unterstützen Menschen durch verschiedene materielle, regulierende, und kulturelle Beiträge, wie beispielsweise Holz, Kohlenstoffspeicherung oder Naherholung. Im wissenschaftlichen Diskurs wurde die Bereitstellung dieser Beiträge lange als kostenlose Dienstleistung der Natur betrachtet. Tatsächlich werden Beiträge der Natur für die Menschen durch eben diese mittels verschiedener anthropogener Kapitalien koproduziert. Menschliche Fähigkeiten, Wissen oder körperliche Arbeit sind hierbei als Humankapital beschrieben. Zwischenmenschliche Beziehungen sowie formelle und informelle Institutionen werden als Sozialkapital bezeichnet, während Maschinen und Infrastruktur als physisches Kapital betrachtet werden. Geldmittel, die zur Koproduktion von Beiträgen der Natur genutzt werden, werden als Finanzkapital bezeichnet. Wälder, ihre Beiträge für die Menschen, sowie die beschriebenen Kapitalien werden in verschiedenen Steuerungsprozessen, genannt Governance, von einer Vielzahl an Akteur*innen auf unterschiedlichen Ebenen beeinflusst. Governance kann mittels verschiedener Modi ausgeübt werden und somit hierarchisch, basierend auf wissenschaftlichen oder technischen Argumenten, kollaborativ oder basierend auf finanzieller Unterstützung sein. Die grafische Zusammenfassung auf der folgenden Seite stellt dar wie Governance auf verschiedenen Ebenen die Koproduktion von Beiträgen der Natur für die Menschen beeinflusst.

Wenngleich die Koproduktion eine stetig wachsende Aufmerksamkeit im wissenschaftlichen Diskurs erfährt, sind die Einflüsse von Governance auf diesen Prozess bislang wenig beachtet worden. Um diese Forschungslücke zu schließen, nähert sich die vorliegende Dissertation der Thematik aus drei Perspektiven: Forschung, Policy und Praxis. Diese Dissertation besteht aus fünf Kapiteln. Das erste Kapitel stellt einen theoretischen Rahmen für die folgenden vier Kapitel dar. Die Forschungsperspektive untersucht, inwiefern die wissenschaftliche Literatur sich mit der Governance von koproduzierten Beiträgen der Natur für den Menschen befasst hat (Kapitel II) und zeigt konzeptionelle, forschungspraxisorientierte sowie thematische Herausforderungen für künftige Forschung auf (Kapitel V). Die Policy- sowie die Praxisperspektive befassen sich mit der Koproduktion von Beiträgen der Natur für die Menschen in drei Fallstudiengebieten in Deutschland. Kapitel III analysiert Policydokumente, um festzustellen, inwiefern verschiedene Governance-Ebenen mittels dieser die anthropogenen Kapitalien in der Koproduktion steuern. Kapitel IV stellt mittels sozialer Netzwerkanalyse, die auf Interviews basiert, fest welche Akteure zentral für das Management verschiedener anthropogener Kapitalien in der Bereitstellung von Beiträgen der Natur für die Menschen sind.

Die Ergebnisse dieser Dissertation lassen darauf schließen, dass die Governance anthropogener Kapitalien in der Bereitstellung von Beiträgen der Natur für die Menschen in drei Themenbereiche zu unterteilen ist. Erstens werden Geldströme genutzt, um andere anthropogene Kapitalien in der Bereitstellung materieller Beiträge zu steuern. Zweitens werden regulierende Beiträge kollaborativ von einer Vielzahl an Akteuren gesteuert. Drittens tragen Schutzgebiete zur Koproduktion von kulturellen Beiträgen bei, indem sie Naturräume schützen und gleichzeitig die Infrastruktur für Besucher*innen bereitstellen. Diese Ergebnisse haben Implikationen für Forschung, Entscheidungsträger*innen und Praxisakteur*innen. Erstens sollte zukünftige Forschung untersuchen, inwiefern

verschiedene Naturwertvorstellungen Entscheidungen über die Nutzung bestimmter anthropogener Kapitalen beeinflussen und wie Entscheidungsträger*innen mittels Governance nachhaltige Formen der Koproduktion unterstützen können. Zweitens sollten Entscheidungsträger*innen feststellen, inwieweit Politiken (Policies) zu einer nachhaltigen Koproduktion beitragen können, indem Zielkonflikte zwischen anthropogenen Kapitalien und Beiträgen der Natur für den Menschen minimiert werden. Drittens können Praxisakteur*innen die Ergebnisse dieser Dissertation nutzen, um auf ihre finanzielle Abhängigkeit von materiellen Beiträgen der Natur aufmerksam zu machen und Unterstützung für ihre Arbeit fordern die regulierende und kulturelle Beiträge befördert.

Grafische Zusammenfassung



Grafik: Governance von koproduzierten Beiträgen der Natur für die Menschen. Governance von lokaler bis supranationaler Ebene beeinflusst die Interaktion von anthropogenen Kapitalien und Natur in der Bereitstellung von Beiträgen von der Natur für die Menschen mittels vier Modi. Diese sind hierarchische, wissenschaftlich-technische und adaptive-kollaborative Governance, sowie die Steuerung von strategischem Verhalten (Primmer et al., 2015). Angepasste Grafik aus Isaac et al. (2023).

Preface

This dissertation, which consists of five chapters, investigates how governance influences the co-production of nature's contributions to people (NCP) in forests. Chapters II to V are individual papers either published (Chapters II, III, and V) or a manuscript about to be submitted (Chapter IV). Chapter I provides a framework for Chapters II to V delineates the need for and fundamental concepts of this dissertation, describes the methodological approach and case study sites, presents the key findings, and discusses these to reach overall conclusions. Chapters II, III, and V are formatted according to the journal standard in which they were published. Chapter IV is formatted in line with the journal requirements for People and Nature.

The appendix to this dissertation contains an overview table highlighting my contributions to each of these papers, the supplementary materials for each chapter, and a declaration of independence for my work on this dissertation. Each supplementary material is formatted according to the respective journal style. The additional publications I have contributed to as a co-author are not attached to this dissertation but listed on page V.

List of publications

Chapter II
Isaac, R., Kachler, J., Winkler, K.J., Albrecht, E., Felipe-Lucia, M.R., Martín-López, B., 2022. Governance to manage the complexity of nature's contributions to people co-production, in: Advances in Ecological Research. Elsevier.
https://doi.org/10.1016/bs.aecr.2022.04.009

Chapter III
Isaac, R., Hofmann, J., Koegst, J., Schleyer, C., Martín-López, B., 2024. Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis, in: Environmental Science & Policy 152.
https://doi.org/10.1016/j.envsci.2023.103657

Chapter IV
Isaac, R., Cumming, G.S., Felipe-Lucia, M.R., Kachler, J., Martín-López., B. The forest beyond the trees: a network on governing nature's contributions to people co-production. Manuscript in preparation.

Chapter V
Isaac, R., Albrecht, E., Felipe-Lucia, M.R., Piquer-Rodríguez, M., Winkler, K.J., Martín-López, B., 2023. Governing the co-production of nature's contributions to people: the road ahead, in: Advances in Ecological Research. Elsevier.
https://doi.org/10.1016/bs.aecr.2023.10.001

List of additional publications

Isaac, R., Kachler, J., Martín-López, B., Felipe-Lucia, M.R., 2022. Fieldwork Protocol Effects of land management on the Supply and Distribution of ecosystem services (ESuDis). https://doi.org/10.13140/RG.2.2.24291.84006

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 pan3.10493. https://doi.org/10.1002/pan3.10493

Kachler, J., Benra, F., Bolliger, R., **Isaac, R.**, Bonn, A., Felipe-Lucia, M.R., 2023. Can we have it all? The role of grassland conservation in supporting forage production and plant diversity. Landsc Ecol. https://doi.org/10.1007/s10980-023-01729-4

Kachler, J., **Isaac, R.**, B., Bonn, A., Felipe-Lucia, M.R., Martín-López, B., 2023. Intrinsic, instrumental, and relational values behind NCP preferences of nature visitors in Germany. *Under review with Ecosystems and People.*

Albrecht, E., **Isaac, R**., Räsänen, A., Legal and political arguments on aquatic ecosystem services – A case study on Kemi River basin, Finland. *Under review with Ecosystem Services*

List of abbreviations

ANOVA	Analysis of Variance
ESuDis	Effects of land management on the supply and distribution of ecosystem services
EU	European Union
HCA	Hierarchical Cluster Analysis
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
MCA	Multiple Correspondence Analysis
NCP	Nature's Contributions to People
NGO	Non-governmental Organisation
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta Analysis
RDA	Redundancy Analysis
RQ	Research Question
SRQ	Sub-research Question
UNESCO	United Nations Educational Scientific and Cultural Organization

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Chapter I

Governing anthropogenic assets for nature's contributions to people co-production in forests: the framework

Roman Isaac

1. Introduction

Forests are multifunctional and provide multiple nature's contributions to people (NCP) (Díaz et al., 2018; Felipe-Lucia et al., 2018; Teben'kova et al., 2020). These include "all contributions, both positive and negative of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life" (Díaz et al., 2018, p. 270). NCP and how people obtain them are context-specific depending on their relationship with nature (Díaz et al., 2018; IPBES, 2022). The NCP concept encompasses but goes well beyond the ecosystem services classification and was introduced within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to integrate plural perspectives on human nature relationships (Kadykalo et al., 2019). Additional to acknowledging the context-specificity of NCP, IPBES proposed a generalising perspective that differentiates between material, regulating and non-material NCP (Díaz et al., 2018). In forests, material NCP are either wood-based, for example, timber as building material or firewood, or non-wood based as wild edible plants, such as mushrooms, wild garlic, or berries (Sheppard et al., 2020). Forests provide a range of regulating NCP, such as carbon storage, erosion control, or water cycling (Seidl et al., 2019). Forests, moreover, provide a broad range of non-material NCP by representing spaces of inspiration and recreation as well as spiritual sites that support people's identities and heritage (Gould et al., 2014).

For a long time, NCP and ecosystem services have been regarded as a "free gift of nature" (Spangenberg et al., 2014, p. 41). In fact, they are influenced by human agency and co-produced by an interplay of natural and anthropogenic assets, also known as capitals (Díaz et al., 2015; Lele et al., 2013; Palomo et al., 2016). Anthropogenic capitals include people's knowledge and skills, rules and norms, machinery and infrastructure, as well as financial assets (Palomo et al., 2016). According to the IPBES conceptual framework various forms of governance and institutions influence nature, its' contributions to people, and the anthropogenic capitals co-producing these (Díaz et al., 2015). Governance differs to government as it refers to all formal and informal arrangements in which state and non-state actors interact to govern (Bevir, 2012). Institutions refer to "the 'rules of the game' that arise

from formal and informal norms and rules, and organisational structures" (Boyd and Folke, 2011, p. 3). While it is context-depended how governance and institutions affect the interplay of natural and anthropogenic capitals, they ultimately influence the extent to which NCP can support human quality of life (Díaz et al., 2015).

This dissertation investigates the role of governance in the co-production of NCP by focusing on forests, which are subject to sometimes conflicting demands, making their governance and management highly debated. Thus, considering various perspectives on forests and their contributions is essential. Hence, understanding the scientific perspective is equally important as considering the political discourse and practitioners' knowledge. This dissertation provides insights into these perspectives to grasp their vantage points better. In this section, I draw upon an extensive body of research on governing forests and their contributions to people (e.g., Arts, 2014; Juerges et al., 2020; Mann et al., 2022; Primmer et al., 2021) and highlight the emerging field of NCP co-production (Kachler et al., 2023b) to provide an overview of the scientific context for this dissertation. In the following, I will introduce the NCP co-production concept and their governance (1.1) and delineate the debate on governing forest NCP (1.2) to identify three specific research gaps addressed by this dissertation (1.3.). In the following sections, I will then outline this dissertation's research approach (2.), the findings and contributions (3.), discuss these findings (4.), and conclude (5.).

1.1 Governing the co-production of nature's contributions to people

The co-production of nature's contributions to people refers to the interplay of natural capital with anthropogenic capitals and has gained increasing attention as an emerging research field in the last decade (Kachler et al., 2023b). Whilst early conceptualisations have focussed on the role of human agency for NCP provision (Lele et al., 2013; Spangenberg et al., 2014), recent research has aimed to unravel the complex human-nature interactions along the co-production process more thoroughly (e.g., Bruley et al., 2021; Lavorel et al., 2020; Rieb et al., 2023). For example, Lavorel et al. (2020, p. 3) define NCP co-production as the "emergence of benefits from nature to people through multiple, long-term and

dynamic socio-ecological interactions and the associated interplay of natural and human-derived capitals". Palomo et al. (2016) specify the different capitals when referring to natural capital as all resources provided by nature that contribute to "maintain life on Earth and human well-being" (p. 248). Anthropogenic capitals encompass human, social, physical (manufactured), and financial capital (Box 1). Human capital in the context of forest ecosystems, for example, is embodied in forest management practices that support the micro-climatic regulation (Lavorel et al., 2020), while collaboration between forest owners in the marketing of timber is an example of social capital (Korhonen et al., 2012). Physical capital refers to the use of specific machinery or tools to harvest timber (Fischer and Eastwood, 2016), while financial capital in forests is mainly linked to revenue generated by selling timber but may include subsidy schemes to promote other forest NCP in the future (Mann et al., 2022). Categorising the different anthropogenic capitals is helpful to disentangle the complex human nature interactions along the co-production process as it generates an understanding of how and by which means human activity substitutes natural capital in the provision of NCP (Palomo et al., 2016).

BOX 1. Anthropogenic capital types

Human capital refers to people's capabilities including health, informal knowledge, formal knowledge, skills, motivation, and labour that can yield a flow of NCP.
Social capital includes all intangible assets associated with interactions between people including formal and informal networks, trust, and formal and informal institutions required for enhancing the flow of NCP.
Physical capital refers to technological or manufactured assets that contribute to the flow 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 that contribute to the flow of NCP.

Based on Palomo et al. (2016) and Goodwin (2003)

The first research gap of this dissertation concerns the interlinkages between governance and NCP co-production that still need to be addressed by research (Gap 1; Table 1). Similar to the growing interest in the co-production of NCP, research has increasingly focussed on the governance of NCP or ecosystem services since the Millennium Ecosystem Assessment in 2005 (Winkler et al., 2021). Governance of NCP or ecosystem services "refers to the

process by which a range of actors (e.g. government, resource users, environmental groups and private entities make decisions that influence the use of ecosystem derived goods and services" (Metzger et al., 2020, p. 2). Research on NCP governance has introduced many concepts from the general governance literature (Winkler et al., 2021). Governance processes can be polycentric and co-ordinate various centres of power (e.g., Morrison et al., 2019; Thiel et al., 2019), stretch across multiple spatial, temporal, and administrative levels (Hooghe and Marks, 2010), and may include diverse yet intersecting modes of governance (Primmer et al., 2015). Research on NCP and ecosystem services has employed various approaches to study these processes (Sattler et al., 2018; Winkler et al., 2021). For example, a framework proposed by Primmer et al. (2015) differentiates between hierarchical, scientific-technical, and (adaptive-) collaborative governance, as well as the governing of strategic behaviour, to grasp how decision-making processes affect NCP and ecosystem services (Box 2). It thereby aims for a holistic analysis of NCP governance as these modes consider who is making decisions based on what arguments (Primmer et al., 2015). Despite an increasing body of literature on the governance of NCP (Winkler et al., 2021) and the central role of governance in the IPBES conceptual framework (Díaz et al., 2015), its effects on the interplay between natural and anthropogenic capitals in the co-production of NCP remain unclear.

BOX 2. Five modes of governing nature's contributions to people. Based on Primmer et al. (2015) and adapted from Isaac et al. (2022, p. 8).

Hierarchical governance concerns regulations that influence NCP and the other modes of governance (Primmer et al., 2015). It is executed by via formal institutions, which exist mainly in the form of policies (e.g., frameworks, laws, regulations) that directly affect NCP or the other governance modes. As interdependencies between policies across governance levels exist, hierarchical governance is often studied in multi-level contexts, and hence, often linked to scale mismatches taking place when ecosystem boundaries do not match with the administrative units' borders (Borgström et al., 2006; Winkler et al., 2021).

Scientific-technical governance refers to decision-making based on scientific and technical arguments (Primmer et al., 2015). Experts, who are not necessarily scientists, influence decision-making and play a vital role in this process. The underlying expectation for scientific-technical governance is that effective dissemination of scientific knowledge leads to better governance (Huth and Possingham, 2011; Sutherland et al., 2004). Land-use planning serves as an example for this governance mode as it incorporates scientific arguments when making decisions about potential trade-offs between NCP (Paavola and Hubacek, 2013).

Collaborative governance stresses the importance of collective learning and bottom-up participatory processes that embrace diverse stakeholder perspectives (Primmer et al., 2015), as these are often considered to contribute positively to ecological outcomes (Bäckstrand et al., 2010). Hence, collaborative governance is best executed when based on open and transparent processes of collective problem-solving (Newig and Fritsch, 2009).

Adaptive governance increases the responsive capacity to changing circumstances, including changing societal values (Burkhard et al., 2012). Examples are stewardship approaches to ecosystems (Chapin III et al., 2015; Olsson et al., 2008) or approaches that promote local learning (Cork et al., 2006).

Governing of strategic behaviour features the potential of governance arrangements and the interactions between them to be transformative (Primmer et al., 2015). It refers to market-based or commercial approaches, such as in Payments for ecosystem services (PES schemes) (see e.g., Börner et al., 2010; Rival, 2010; Van Hecken and Bastiaensen, 2010). This implies the aim to influence policymaking processes through lobbying to affect policies and protect particular interests (Newig and Fritsch, 2009; Primmer et al., 2015). Governing of strategic behaviour can nudge behaviour in a desired direction (Primmer, 2011).

1.2 Governing forests and their contributions to people

Forests and their contributions to people are governed via diverse governance initiatives. For example, Arts and Buizer (2009, p. 344) describe forest governance as "network-like arrangements of public and private actors, self-regulation by market organizations, public-private partnerships, emission trading schemes, covenants, certification programs, etc.". Whilst forest governance remains a contested concept due to many different interpretations (Arts, 2021), it is challenged to sustain the provision of multiple NCP by a broad range of societal demands, increased pressures due to climate change, or conflicting

interests (Winkel et al., 2022). Hence, forest governance needs to ensure that forests are managed sustainably and mediate between diverging interests to support the provision of multiple forest NCP (Hernández-Morcillo et al., 2022; Lazdinis et al., 2019). Understanding how forests are governed across multiple levels is imperative when addressing these challenges (Fig. 1).

The second research gap of this dissertation stresses that the effects of policy on anthropogenic capitals in the co-production of forest NCP remain unknown (Gap 2; Table 1). For example, in the European context, governance spans multiple levels ranging from the local to the supra-national level of the European Union and beyond (Arts, 2014; Hooghe et al., 2001). Policies remain an essential instrument for governing NCP within the European Union's multi-level governance system (Bouwma et al., 2018). In contrast to agricultural systems, the competence to govern forests and their contributions solely lies with the EU's member states and their subordinate levels (Primmer et al., 2021; Winkel et al., 2022). The influence of policies on the provision of forest NCP has been studied across policy fields, EU member states, and governance levels (e.g., Aggestam and Pülzl, 2018; Beland Lindahl et al., 2023; Hochmalová et al., 2021; Primmer et al., 2021). Research has not only shown that policies recognise material, regulating, and non-material NCP (Elomina and Pülzl, 2021; Primmer et al., 2021) but uncovered that conflicting policy goals (Blattert et al., 2022) and favouring specific forest management strategies depending on national contexts (Beland Lindahl et al., 2023) might lead to potential trade-offs between forest NCP. Despite implicitly touching upon various anthropogenic capitals, for example, by referring to access rights (Hochmalová et al., 2021) or subsidies (Sotirov and Storch, 2018), research has so far neglected the role of policies in governing these capitals. However, understanding how decision-making drives the use of anthropogenic capitals for NCP co-production is needed to ensure the sustainability of these processes.

The third research gap addressed by this dissertation concerns the role of actor relationships in governing anthropogenic capitals for the co-production of forest NCP (Gap 3; Table 1). Forest governance reaches beyond government-induced top-down approaches as it involves diverse actors in formal and informal, often polycentric,

governance settings (Arts, 2021). Research has aimed to disentangle the complex actor relationships governing forest NCP in various contexts (e.g., Górriz-Mifsud et al., 2017; Keskitalo et al., 2014; Korhonen et al., 2012). For example, communities manage forests collectively and in collaboration with external actors to provide multiple NCP, which are either used locally or sold to markets (Friedman et al., 2020; García-Amado et al., 2012). Moreover, conflicts between interests and beneficiaries of different NCP exist, and thus, collaborative efforts by actors in different sectors and across governance levels are essential for successfully governing forests (Keskitalo et al., 2014). While research has made implicit references to anthropogenic capitals when studying actor networks in forest governance (e.g., Górriz-Mifsud et al., 2017, 2016), it lacks a coherent approach employing the co-production concept to more deeply understand how governance affects the use of anthropogenic capitals explicitly.

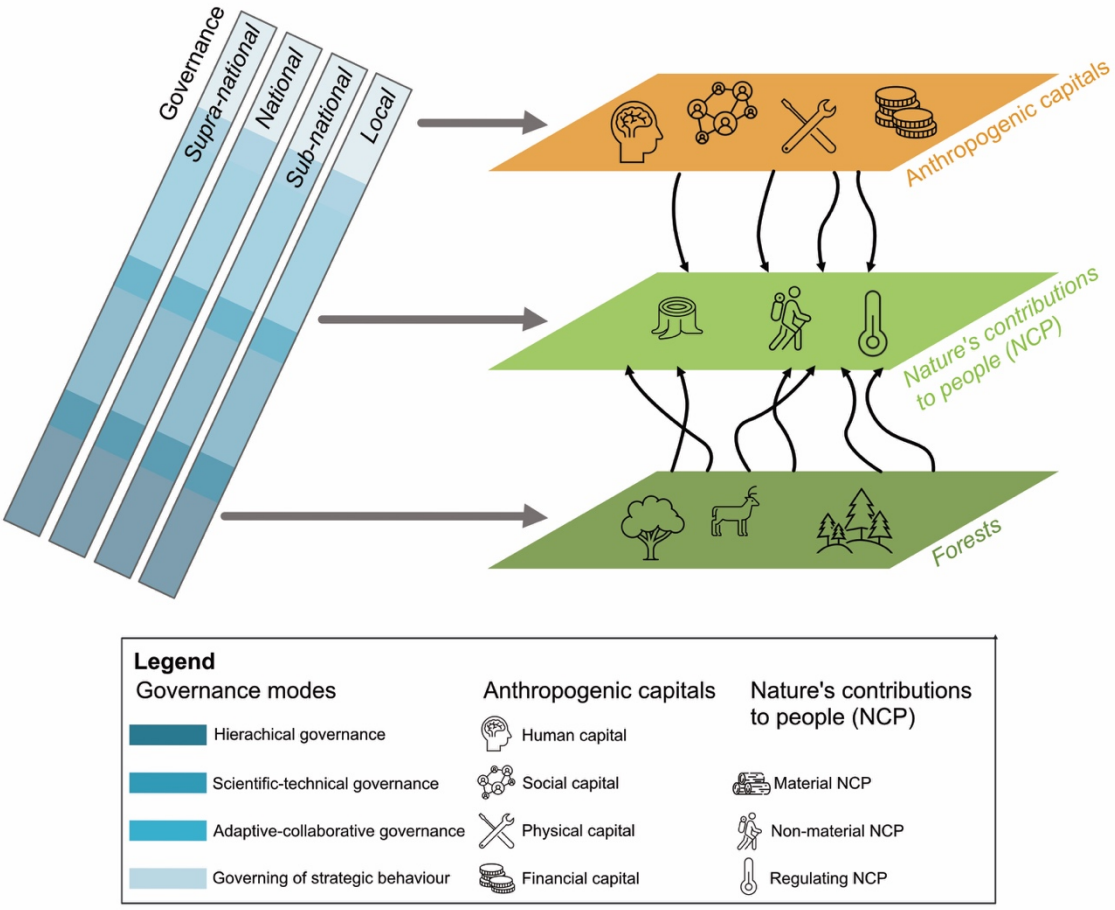

FIGURE 1 Governing the co-production of nature's contributions to people. Governance levels from the local to the supra-national affect the interplay of forests and anthropogenic capitals in the co-production of nature's contributions to people by using four intersecting governance modes, i.e., hierarchical, scientific-technical, and adaptive-collaborative governance, as well as the governing of strategic behaviour (Primmer et al., 2015). Figure adapted from Isaac et al. (2023).

1.3 Research aim and research questions

This dissertation aims to contribute to the emerging field of NCP co-production by providing a better understanding of how governance influences the interplay between natural and anthropogenic capitals in the provision of forest NCP and identify opportunities for future research to inform governance for sustainable forms of NCP co-production. To do so, I seek to address the research gaps outlined above by addressing four research questions:

- RQ1: *How does the scientific literature portray the governance of nature's contributions to people co-production?*
- RQ2: *How do different governance levels affect the co-production of nature's contributions to people in forests via policy?*
- RQ3: *Who are the relevant actors in governing the co-production of nature's contributions to people in forests?*
- RQ4*: How can research contribute to improving governance for sustainable forms of nature's contributions to people co-production?*

Table 1 illustrates how the specific research questions and chapters of this dissertation address each research gap.

TABLE 1 Overview on research gaps, research questions, and contributing papers. The tree icon (🌳) indicates which gap and research question are addressed by a specific chapter.

				Chapter			
Research gap		**Research question**		**II**	**III**	**IV**	**V**
Gap 1	The interlinkages between governance and NCP co-production are under explored.	RQ1	*How does the scientific literature portray the governance of nature's contributions to people co-production?*	🌳			
		RQ4	*How can research contribute to improving governance for sustainable forms of nature's contributions to people co-production?*				🌳
Gap 2	The effects of formal governance on the interplay of natural and anthropogenic capitals in the co-production of forest NCP are unknown.	RQ2	*How do different governance levels affect the co-production of nature's contributions to people in forests via policy?*		🌳	🌳	
Gap 3	The role of actor relationships in governing the co-production of forest NCP remains unknown.	RQ3	*Who are the relevant actors in governing the co-production of nature's contributions to people in forests?*			🌳	

2. Research approach

This section outlines the research approach taken for this dissertation. First, I elaborate on the research design and how the research questions are addressed by the respective chapters of this dissertation (2.1). Second, I provide some information on the context of this dissertation (2.2) and the case study sites (2.2). Lastly, I consider some ethical implications concerning the empirical work within this dissertation (2.3).

2.1 Research design

The co-production of NCP is influenced by actors across governance levels, geographical scales, and sectors. Therefore, I follow the ontological position of constructivism, which is based on the notion that social reality is shaped by social actors, influenced by their interactions, and differs depending on their perspective (Bryman, 2016). To understand the

diverse vantage points on governing NCP co-production, I address the research gaps from three focal perspectives: research, policy, and practice (Figure 2). First, I focus on the research perspective and use a conceptual approach by reviewing the scientific literature to understand how research portrays the governance of NCP co-production and answer RQ1 (Chapter II). Second, I approach the topic empirically from a policy perspective by analysing policy documents across multiple governance levels to understand how formal governance addresses anthropogenic capitals in forest NCP co-production and answer RQ2 (Chapter III). Third, I focus on practitioners by conducting social network analysis (SNA) based on forest actor interviews, thus following an empirical approach to unravel the relationships between actors who co-produce forest NCP and thus answer RQ3 (Chapter IV). Fourth, I follow a conceptual approach to investigate thematic, conceptual, and practice-oriented gaps and challenges for research on governing NCP co-production and to identify how and with which methods future studies can employ to contribute to policy and practice that foster more sustainable forms of co-production (RQ4; Chapter V). Figure 3 provides an overview organised by the focal perspectives highlighting the research questions, the data and methods used, and how they relate to each chapter of this dissertation.

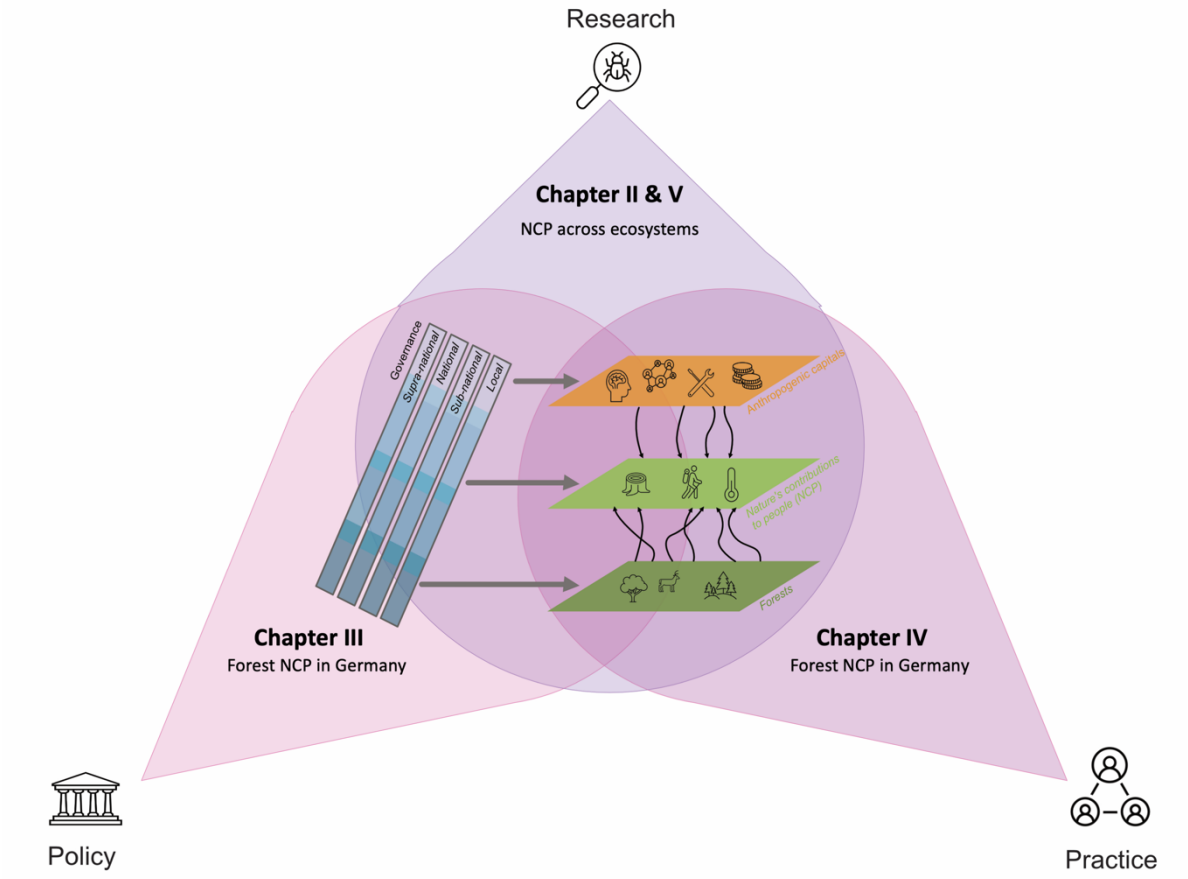

FIGURE 2 Seeing the forest beyond the trees. Approaching the governance of nature's contributions to people (NCP) co-production from three perspectives: research, policy, and practice. The research perspective focuses on NCP across ecosystems and the world, while the policy and practice perspectives focus on forest NCP in German case study sites.

Chapter II is based on the paper *Governance to manage the complexity of nature's contributions to people co-production* which was published in the Advances in Ecological Research Special Issue on Pluralism in Ecosystem Governance in 2022 (Holzer et al., 2022; Isaac et al., 2022). For the systematic literature review in this chapter I followed the Preferred Reporting Items for Systematic Reviews and Meta Analysis (PRISMA) flow diagram to identify publications studying the interplay of natural and anthropogenic capitals, the co-produced NCP, and their governance (Page et al., 2021). Second, I used NCP and ecosystem services governance publications previously identified by Winkler et al. (2021) that referred to NCP co-production. In total, I conducted a qualitative content analysis (Preiser et al., 2021) of 45 publications using a deductive coding set based on the 18 generalised NCP categories described by Díaz et al. (2018), the four anthropogenic capital types defined by Palomo et al. (2016), and the five modes of governance proposed by

Primmer et al. (2015). Further, I performed a hierarchical cluster analysis (HCA) and a multiple correspondence analysis (MCA) to identify three clusters in the scientific literature that portrayed how governance modes affect the use of anthropogenic capitals in NCP co-production.

Chapter III is based on the manuscript *Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis* and was published in Environmental Science and Policy in 2024 (Isaac et al., 2024). For the policy document analysis (Cardno, 2018), I followed an iterative process to identify 76 forest-related policy documents across policy domains, e.g., forestry, biodiversity conservation, agriculture, etc., and governance levels, from the local case study to the EU. Similar to Chapter II, I conducted a qualitative content analysis (Preiser et al., 2021) using a coding set based on the five modes of governance (Primmer et al., 2015) and the four types of anthropogenic capitals (Palomo et al., 2016), but focussed on ten forest-related NCP covering material, regulating, and non-material NCP. Based on the coded data, I performed a Redundancy Analysis (RDA) (Rao, 1973) to identify six archetypes of governing anthropogenic capitals in the co-production of forest NCP across governance levels. Additionally, I performed an Analysis of Variance (ANOVA) to test whether these archetypes differed between the three case study sites.

Chapter IV is based on the manuscript *The forest beyond the trees: a network perspective on governing nature's contributions to people co-production* and is in preparation for submission to People and Nature (Isaac et al., in preparation). For this paper, I conducted a social network analysis (Borgatti et al., 2022; Carrington and Scott, 2011) based on 39 expert interviews with foresters and conservation managers in three case study sites (Shackleton et al., 2021). Further, I used qualitative coding for the interview transcripts to grasp which actors were perceived as most relevant in governing specific anthropogenic capitals in the co-production of forest NCP (Preiser et al., 2021). The social network analysis resulted in four networks for the focal forest NCP, i.e. timber production; creation and maintenance of habitat, climate regulation; and non-material NCP, as well as a combined network. Additionally, I calculated three centrality metrics, i.e., degree centrality,

betweenness centrality, and eigenvector centrality, to determine which actors were most influential in governing anthropogenic capitals in NCP co-production (Borgatti et al., 2022; Hannemann and Riddle, 2011). Finally, I used a non-parametric Kruskal-Wallis test to determine whether there were differences among the actor groups regarding the centrality metrics. First, I tested for differences among actor groups by the forest NCP they co-produced. Second, I tested for differences among actor groups regarding their use of anthropogenic capitals. When the Kruskal-Wallis tests showed significant differences, I used Dunn's pairwise comparison test to assess differences between the actor groups. The test results led to the identification of three patterns of governing anthropogenic capitals in the co-production of forest NCP.

Chapter V is part of a series of outlook papers in Advances in Ecological Research and entitled *Governing the co-production of nature's contributions to people: the road ahead* (Isaac et al., 2023). In this chapter, I identify and elaborate on eight challenges faced by research on governing anthropogenic capitals for NCP co-production. These challenges are conceptual, rooted in research practice, and thematic. By drawing attention to the biases in current and emerging research themes, I showcase how future research could better inform decision-making processes regarding NCP co-production and thus ensure their sustainable provision.

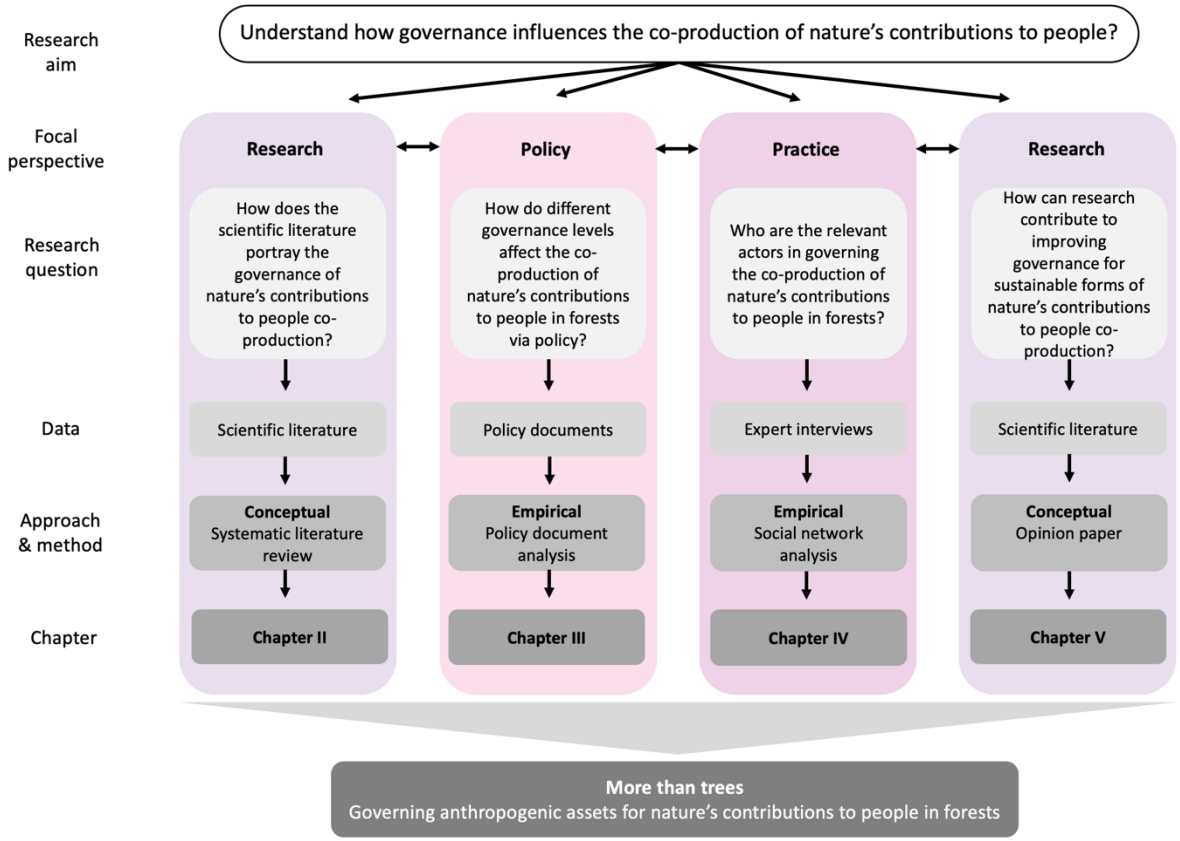

FIGURE 3 Research approach: overview of how each chapter of this dissertation contributes to fulfilling the main aim by using a specific focal perspective and addressing the research questions (RQs) with different approaches and methods. Central arrows indicate that the focal perspectives, i.e., research, policy, and practice, influence each other.

2.3 Case study – Biodiversity Exploratories

This dissertation and the research presented here is embedded in the large-scale and long-term research project platform *Biodiversity Exploratories*, which investigates the impacts of land-use on biodiversity and ecosystem functioning in grasslands and forests (Fischer et al., 2010). The *Biodiversity Exploratories* are funded by the German Research Foundation (DFG). While several studies have investigated the ecological effects of forest management (e.g., Getzin et al., 2012; Gossner et al., 2013; Schall et al., 2018), little research exists on the social aspects of land management (Kachler et al., 2023a; Le Provost et al., 2022; Neyret et al., 2023; Peter et al., 2022). The research presented here was conducted as part of the project *Effects of land management on the Supply and Distribution of ecosystem services* (ESuDis), which aimed to understand how increased land-use intensity and substitution of

natural with anthropogenic capitals affect the supply and distribution of multiple ecosystem services across scales and how governance affected these (ESuDis, 2023).

The *Biodiversity Exploratories* include three rural case study sites across three federal states in Germany: Schorfheide-Chorin in the Northeast (Federal State of Brandenburg), Hainich-Dün in the country's centre (Free State of Thuringia), and Schwäbische Alb in the Southwest (State of Baden-Württemberg) (Fischer et al., 2010) (Figure 4). The sites vary in their location and social and physical parameters. While Schorfheide-Chorin and Hainich-Dün cover relatively large areas, both sites span across approx. 1,300km^2 and are sparsely populated in comparison to other German regions; the Schwäbische Alb is smaller in size (approx. 422km^2) and more densely populated (Table 2) (Fischer et al., 2010). This is due to its location on submontane and montane plateaus in the densely populated southwest of Germany. Forests are important landscape features in all three case study sites. The *Biodiversity Exploratories* monitor 500 forest grid plots of which 13% were unmanaged, 83% managed age-class forests, and 4% selection forests. Hainich-Dün is home to most unmanaged forests (28%) (Fischer et al., 2010).

TABLE 2 Characteristics of the *Biodiversity Exploratories* case study sites. Adapted table from Fischer et al. (2010, p. 276) (a.s.l: above sea level).

Characteristic	**Schorfheide-Chorin**	**Hainich-Dün**	**Schwäbische Alb**
Location in Germany	Northeast	Central	Southwest
Federal state	Brandenburg	Thuringia	Baden-Württemberg
Main protection status	Biosphere Reserve	National Park	Biosphere Reserve
Size	~1,300km^2	~1,300km^2	~422km^2
Altitude a.s.l.	3-140m	285-550m	460-860m
Annual mean temperature	8-8.5°C	6.5-8°C	6-7°C
Annual mean precipitation	500-600mm	500-800mm	700-1,000mm
Human population density	23km^{-1}	116km^{-1}	258km^{-1}

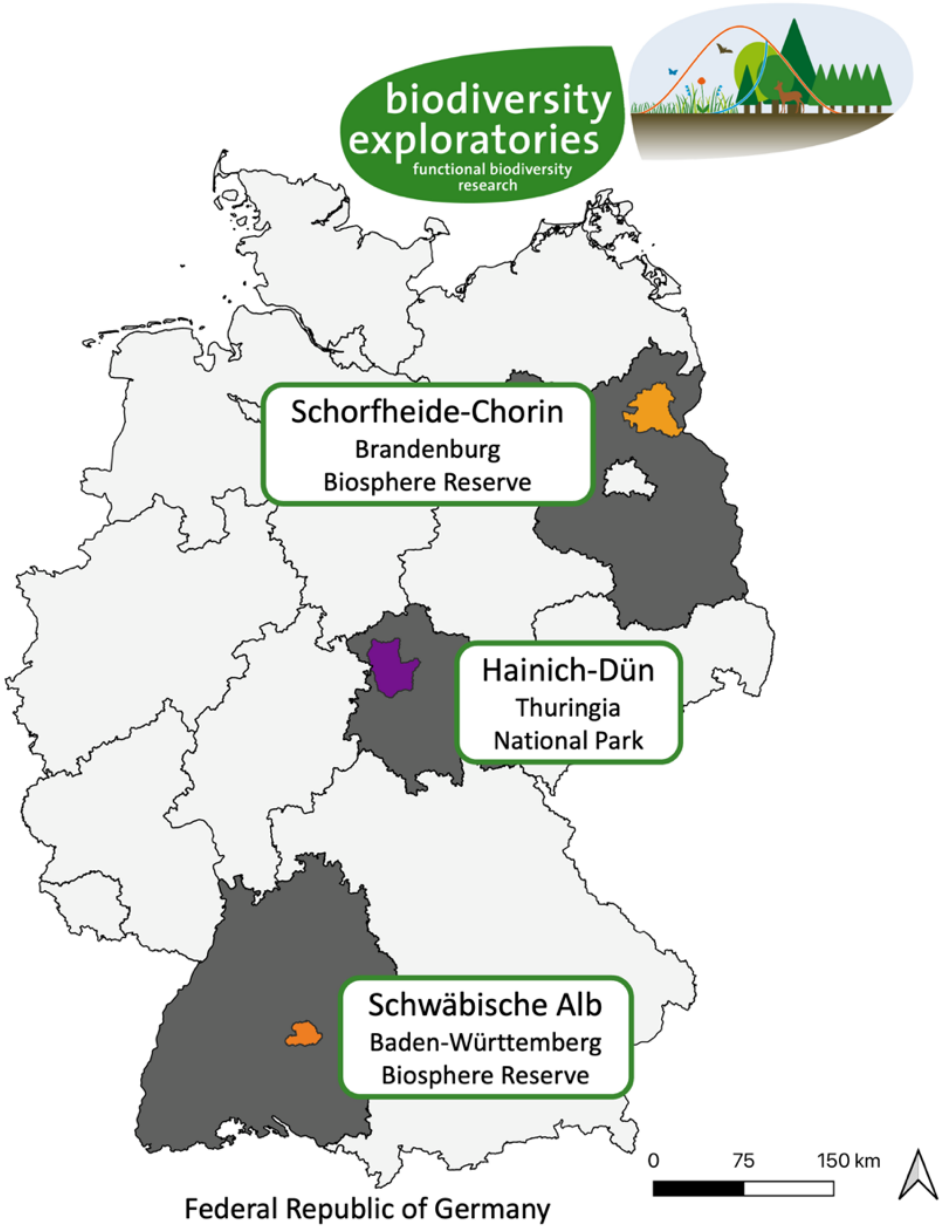

FIGURE 4 The Biodiversity Exploratories case study sites. Schorfheide-Chorin, Hainich-Dün and Schwäbische Alb are shown in their respective federal states across Germany and with the main status of protection for nature conservation. Those sites including UNESCO biosphere reserves are coloured in orange and the one containing a national park in purple. This map based on data provided by the Biodiversity Exploratories Information System (BExIS) (2022) and Esri Deutschland GmbH (2018). Figure author's own.

The three case study sites are embedded in a multi-level governance system spanning from the local to the European level (Grotz, 2012). While decision-making processes at the EU and the German federal (*Bundesrepublik*) level affect all three case study sites, governance may differ between the different federal states (*Bundesländer*) and the respective local levels (Box 3; Figure 4).

BOX 3. Governance levels of case study sides

European refers to the European Union (EU) and policies made by the European Commission and parliament such as directives, regulations and strategies that affect all 27 member states.

Federal refers to policymaking on the German federal level (Bundesebene). Policies apply to all lower governance levels and include laws (e.g. German Forest Law) and regulations (e.g. fertiliser regulation)

State level refers to policies made by the 16 German federal states. For our research, these include Brandenburg, Thuringia and Baden-Württemberg. Policies include laws, regulations, and funding directives.

Local level refers to our three case studies – the Biosphere Reserve Schorfheide-Chorin, the National Park Hainich and the Biosphere Reserve Schwäbische Alb. Policies on this level include management plans. These are however also administered at the state level.

Various protected areas can be found across the case study sites. While Schorfheide-Chorin and Schwäbische Alb are both home to a UNESCO[1] biosphere reserve, the Hainich-Dün exploratory includes the Hainich National Park (Biosphärengebiet Schwäbische Alb, 2023; Landesamt für Umwelt Brandenburg, 2023a; Nationalpark Hainich, 2023). Beyond these landscape-wide protection statuses, Schorfheide-Chorin and Hainich-Dün also include areas that are part of the UNESCO World Heritage site *Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe* (UNESCO, 2023). Furthermore, all case studies include other protected areas, e.g., Natura 2000[2] sites, nature reserves, or landscape protection areas. Thus, decision-making processes regarding nature and its contributions to human wellbeing differ between the sites due to local characteristics.

Schorfheide-Chorin

The area of Schorfheide-Chorin was formally protected in 1990 by one of the last regulations passed in the former German Democratic Republic (GDR, *DDR*) and later recognised as a biosphere reserve by UNESCO (Land Brandenburg, 1990; Landesanstalt für Großschutzgebiete, 1997). A mosaic of agricultural fields, grasslands, peatlands, forests,

[1] United Nations Educational Scientific and Cultural Organization (UNESCO).
[2] Natura 2000 is an EU wide network of areas protected under the EU's Habitats Directive (92/42/EEC) and the Birds Directive (2009/147/EC) (European Commission, 2022).

and lakes characterises the landscape. The area includes 75 villages and 3 towns. Land use in a sustainable way remains to be allowed in 78% of the biosphere reserve (transition zone), whilst 19% of the area is designated for nature conservation (buffer zone). The core zone covers 3% of the area and is continuously monitored (Landesamt für Umwelt Brandenburg, 2023b). Due to the large number of endangered species, the biosphere reserve is also home to 25 of the 36 Natura 2000 sites in the State of Brandenburg (ibid.).

Hainich-Dün

Local people have managed the forests in Hainich-Dün for centuries using the so-called Plenterwald system, which aims to harvest only the largest trees to support natural rejuvenation (Nationalpark Hainich, 2023). The southern part of the Hainich forest had been used as a military training site between 1935/1936 and 1995, which led to minimising land use and increasing deadwood in the area. Ongoing debates on formal protection of the 7500ha large site started in 1993 and culminated in the establishment of the Hainich National Park on December 31, 1997 and opening on February 28, 1998 (Nationalpark-Verwaltung Hainich, 2008). The park is covered by 70% forests, primarily beech, which has also led to its recognition as a World Heritage site by UNESCO (UNESCO, 2023).

Schwäbische Alb

The Biosphere Reserve Schwäbische Alb was recognised as such by UNESCO in May 2009 as the result of a collaborative process involving the State of Baden-Württemberg, three districts, and the cities and municipalities in the area. The landscape is characterised by a small-scale mosaic of agricultural fields, grasslands, and forests that are located on the sub-montane and montane plateau of the Schwäbische Alb. Like the Biosphere Reserve Schorfheide-Chorin, the Schwäbische Alb contains three zones of varying protection status. The core zone covers 3.1% of the area while the buffer zone covers 41.5%. The largest part of the Biosphere Reserve (55.4%) is part of the transition zone. Whilst the Schwäbische Alb itself can be characterised as rural, its closeness to the cities of Stuttgart, Reutlingen, Ulm, and Tübingen, make it an important tourist destination (Land Baden-Württemberg, n.d.).

2.5 Ethical considerations

This dissertation is partially based on interviews with forest actors (Chapter IV). Several ethical aspects must be considered when conducting research with people. First, forests and the NCP they provide are often subject to conflicts between various actors who pursue diverging interests (Eckerberg and Sandström, 2013). These conflicts may not be visible or accessible to grasp for researchers when engaging with practitioners. Second, the *Biodiversity Exploratories* have been conducting research on private and public land since 2006 and depend on the landowners' and administration's permission to continue doing so (Fischer et al., 2010). Thus, any research involving landowners, land managers, or administrative staff must consider these dependencies and avoid negatively affecting granted access rights. Third, interview respondents may provide sensitive, private, or personal information. Data management must thus ensure that all data is anonymised, stored securely, and deleted after data analysis. To address these aspects and ensure thorough protection of private data, the methodological approach of this thesis, including the interview guideline for the ESuDis project, was approved by the Leuphana University's ethics review committee (EB-Antrag 2021-03_Isaac_ESuDis; for letter of approval see Appendix 2).

3. Findings and chapter contributions

This section outlines how each of the following chapters (II-V) seeks to address one of the three research gaps outlined in section one and does so by answering one of the four research questions (Table 4).

Chapter II *Governance to manage the complexity of nature's contributions to people co-production* uses a systematic literature review to understand how the scientific literature has studied the governance of NCP co-production (RQ 1; Table 3). Despite a large body of research on NCP and ecosystem services (Droste et al., 2018) and an increasing number of studies on their governance (Winkler et al., 2021), my literature review revealed that the interplay of natural and anthropogenic capitals has mainly been neglected when studying the governance of nature's contributions to people and ecosystem services. Only a few

publications investigate the governance of NCP co-production explicitly. Research has predominantly focussed on material and regulating NCP and their co-production by varying combinations of anthropogenic capitals, with social capital being the most important. Research mainly studied co-production processes governed by combined governance modes but with a solid hierarchical influence. Moreover, the hierarchical cluster analysis revealed three thematic clusters within research on governing NCP co-production. *Cluster 1* portrays research studying the co-production of material NCP by human and financial capital, which is influenced by the governing of strategic behaviour. *Cluster 2* encompasses research on non-material NCP co-produced by social capital and governed hierarchically at regional and local levels. *Cluster 3* covers research on regulating NCP co-produced by physical capital and governed scientific-technically and collaboratively at the sub-national level. By revealing these clusters, Chapter II addresses research gap one and advances the research field conceptually by connecting governance and NCP co-production.

Chapter III *Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis* seeks to understand how formal governance intends to govern anthropogenic capitals in the co-production of forest NCP (RQ 2; Table 3). To fulfil this aim, I analysed 76 policy documents across governance levels. Whilst previous analyses have shown how policy documents are used to govern forests and their contributions to people (e.g., Beland Lindahl et al., 2023; Hochmalová et al., 2021; Primmer et al., 2021), my analysis revealed that policy documents recognised the importance of anthropogenic capitals for the provision of forest NCP despite not referring to the co-production concept explicitly. The policy documents primarily focussed on material NCP, almost exclusively timber production, and regulating NCP, mainly habitat creation and maintenance, but made some references to non-material NCP. The policy documents predominantly referred to human and social capital in the provision of these NCP and intended to govern the co-production process hierarchically and scientific-technically. Moreover, this chapter contributes to the debate on forest governance and addresses gap two by revealing six archetypes via the Redundancy Analysis. *Archetype 1 Governing of strategic behaviour for regulating NCP* emphasises the importance of governmental payments for the creation and management

of habitat. *Archetype 2 governing habitat management for experiences in nature,* showcases how scientific-technical governance can support the provision of non-material NCP by promoting habitat management. *Archetype 3 governing habitat management for pest control* illustrates that well-managed habitats support natural pest control. *Archetype 4 collaborative governance for timber* highlights the importance of collaboration among forestry actors and institutions across levels in providing timber. *Archetype 5 local governance for experiences in nature* stresses that local governance can support the provision of non-material NCP by establishing recreational infrastructure. *Archetype 6 promoting knowledge for habitat protection,* captures how scientific-technical governance can support regulating NCP by disseminating knowledge. By identifying these six archetypes, Chapter III advances the research on NCP co-production empirically, as the influence of policy documents on NCP co-production was previously under-explored.

Chapter IV *The forest beyond the trees: a network perspective on governing nature's contributions to people co-production* seeks to answer RQ3 by revealing the actors central to governing anthropogenic capitals in the co-production of forest NCP across the three case-study sites (Table 3). Whilst several publications have used social network analysis to understand the governance of forests (e.g., Górriz-Mifsud et al., 2017; Keskitalo et al., 2014; Korhonen et al., 2012; Paletto et al., 2012; Schulz et al., 2018) and NCP co-production (e.g., Albizua et al., 2021; Jericó-Daminello et al., 2021), the analysis performed here unravels how actors across governance levels are connected by anthropogenic capitals when co-producing forest NCP and thereby addresses gap three (Table 3). While some forest NCP, namely timber production, climate regulation, and non-material NCP, depend on a few actors and anthropogenic capitals, the SNA revealed that the creation and maintenance of habitat is co-produced by a range of actors using various anthropogenic capitals. Further, based on a Kruskal-Wallis test, I could reveal three patterns in which forest actors govern anthropogenic capitals to co-produce NCP. *Pattern 1 governance of timber production via financial flows* illustrates how forest owners are connected to other actors via financial capital to support timber production. *Pattern 2 governing knowledge and labour for climate regulation,* emphasises the importance of knowledge sharing among actors and the need for manual labour to support forests' ability to regulate the micro-climate and sequester

carbon. *Pattern 3 governance for habitat management* demonstrates the role of protected areas in creating and maintaining habitat by mediating between diverse interests and enforcing existing regulations. By identifying these patterns, Chapter IV contributes to the research field empirically.

Chapter V *Governing the co-production of nature's contributions to people: the road ahead* contrasts the previous chapters as it assesses the current debate and identifies eight research gaps and challenges for research on the governance of NCP co-production. For one, gaps concerning research practices include expanding the spatio-temporal scope of study sites, accounting for stakeholder diversity, and strengthening evidence-based and collaborative approaches, e.g., co-creation of knowledge, to gain a more nuanced understanding of the social processes behind the co-production of NCP and their governance. Second, conceptual gaps in this realm relate to the challenging distinction between social capital and governance and further investigations into the potentially reciprocal relationship between anthropogenic capitals and NCP. Third, a range of thematic gaps must be addressed for research to support decision-making processes that foster sustainable forms of NCP co-production. These include understanding the polycentric nature of governance arrangements that affect anthropogenic capitals in the co-production process, dealing with conflicts and power asymmetries, exploring the role of plural values in governing NCP co-production, and identifying leverage points to transform unsustainable forms of NCP co-production. This chapter answers RQ4 and adds to filling the first gap by exploring these research gaps and challenges. Thereby, Chapter V provides a conceptual and a societal contribution since it illustrates how research could contribute to improving decision-making processes regarding the co-production of NCP (Table 3).

TABLE 3 Summary of results and contributions to the field by each chapter.

Chapter		Methods	Findings	Contributions	Gap & RQ
II	Governance to manage the complexity of nature's contributions to people co-production	→ Systematic literature review → Qualitative content analysis → Multiple correspondence analysis (MCA) → Hierarchical cluster analysis (HCA)	→ Few publications link governance and NCP co-production. → Three clusters could be identified across publications.	*Conceptual contribution* Better understanding on how research has studied the governance of NCP co-production so far.	Gap 1 RQ 1
III	Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis	→ Policy document analysis → Redundancy analysis (RDA)	→ Policy documents focus on material and regulating NCP, human and social capital, and hierarchical governance. → Six archetypes could be identified across the policy documents.	*Empirical contribution* Better understanding on how policy documents across governance levels intent to govern anthropogenic capitals in the co-production of forest NCP.	Gap 2 RQ 2
IV	The forest beyond the trees: a network perspective on governing nature's contributions to people co-production	→ Semi-structured interviews → Qualitative content analysis → Social network analysis (SNA)	→ Some NCP depend on few actors and capitals for their co-production while others involve many. → Three patterns representing actor and capital constellations were identified.	*Empirical contribution* Identification of key actors who drive the use of specific anthropogenic capitals in the co-production of forest NCP and a better understanding of linkages based on these capitals.	Gap 3 RQ 3
V	Governing the co-production of nature's contributions to people: the road ahead	→ Conceptual paper	→ Eight thematic, conceptual, and research practice related gaps and challenges need to be addressed by future research to support governance for the sustainable co-production of NCP.	*Conceptual and societal contribution* Identification of gaps in the existing literature and proposing ways forward for research to inform decision-making for sustainable NCP co-production.	Gap 1 RQ 4

4. Discussion

In this section, I discuss how the following chapters (II-V) are interlinked and contribute to a better understanding of governing NCP co-production (4.1). Then, I reflect upon the research process to identify challenges and opportunities (4.2). Finally, I consider potential implications for policy and practice and future research (4.3).

4.1 Seeing the forest beyond the trees

The interplay of natural and anthropogenic capitals in the co-production of nature's contributions to people is governed by a variety of actors across spatial and governance levels and by different modes of governance (Díaz et al., 2015; Palomo et al., 2016; Primmer et al., 2015). To account for the diversity of governance arrangements, I approached the research gaps in this dissertation from three focal perspectives: research, policy, and practice. While Chapters II and V relate to the governance of NCP co-production across ecosystems and the globe, Chapters III and IV focus on forests in three case study sites (Figure 4).

The research perspective illustrated that the governance of NCP co-production remains underrepresented in the scientific literature (Chapter II) and explored several gaps related to conceptual, thematic, and research practice (Chapter V). Concerning RQ1, I showed in Chapter II that the scientific literature might recognise the effects of governance on the interplay of natural and anthropogenic capitals but still needs to integrate the co-production concept when studying NCP governance. The concept's minimal uptake in the scientific literature may be due to the conceptual ambiguities and lack of tangibility for decision-makers, as identified in Chapter V (in response to RQ4).

For the policy perspective, I demonstrated in Chapter III and in response to RQ2 that policy documents across governance levels account for anthropogenic capitals in the light of forest NCP provision but need to recognise the co-production concept explicitly and acknowledge that formal governance can steer co-production processes intentionally. Thus, policy documents do not aim to resolve potential trade-offs between NCP and between anthropogenic capitals that may occur when favouring specific capitals (Palomo et al., 2016).

Examining the role of practitioners in governing NCP co-production in forests revealed how actors are connected via specific anthropogenic capitals even though the co-production concept itself may not be incorporated in practice. In Chapter IV and in response to RQ3, I thus demonstrated that forest actors in the three case study sites are less connected and by fewer anthropogenic capitals for the co-production of timber, climate regulation, and non-material NCP, than for the creation and maintenance of habitat.

The focal perspectives of this dissertation may differ in their approach to the co-production concept and their geographical scope but display similarities regarding how anthropogenic capitals are governed for NCP co-production. The analyses for this dissertation revealed three clusters for the research perspective (Chapter II), six archetypes for the policy perspective (Chapter III), and three patterns for the practice perspective (Chapter IV). Three distinct themes emerge when comparing the combinations of anthropogenic capitals and NCP and how they are governed across perspectives (Figure 5).

Themes of governing NCP co-production	Nature's contributions to people (NCP)	Anthropogenic capitals	Governance modes	Global	German case studies	
				Research	Policy	Practice
Theme I Money makes the world go round	Material NCP	Human capital Social capital Financial capital	Collaborative governance Governing of strategic behaviour	Cluster 1	Arche-type 4	Pattern 1
Theme II Conservation and collaboration to support regulating NCP	Regulating NCP	Human capital Social capital Physical capital Financial capital	Hierarchical governance Scientific-technical governance Collaborative governance	Cluster 3	Arche-types 1, 3, and 6	Patterns 2 & 3
Theme III Governing protected areas for non-material NCP	Non-material NCP	Human capital Social capital Physical capital	Hierarchical governance Scientific-technical governance	Cluster 2	Arche-types 2 and 5	none

FIGURE 5 Themes of governing the co-production of nature's contributions to people (NCP). The clusters, archetypes, and patterns found in the respective focal perspectives of this dissertation, research, policy, and practice (in purple), display three congruent themes in which different modes of governance (in blue) influence anthropogenic capitals (in orange) involved in the co-production of NCP (in green).

Theme I: Money makes the world go round

The first theme illustrates the importance of financial capital as an intermediary tool for governing the co-production of material NCP (Figure 5). The research perspective showed that financial capital connects different actors and facilitates using other anthropogenic capitals to co-produce material NCP (Chapter II, Cluster 1). In forests, for example, decision-making still strongly depends on the marketisation of timber to generate revenue instead of monetising regulating and non-material NCP (Mann et al., 2022). The practice perspective illustrated how financial capital connects forest owners with other actors and facilitates the use of other anthropogenic capitals (Chapter IV, Pattern 1). For example, revenue is used to pay forest managers and contractors who employ their skills, knowledge, labour, and machinery to harvest timber. In Germany, the focus on sustainable timber production is supported by a coalition of forest owners, forest industry, and state forest agencies. At the same time, environmental actors, such as NGOs, have pushed for more biodiversity-focused management (Sotirov and Storch, 2018). However, the "German model of integrative multifunctional forestry" has been described as fostering societal demands for non-timber-based NCP, e.g., wild edible plants or recreation, through the use of forests (Borrass et al., 2017). In line with Sotirov and Storch (2018), the policy perspective revealed that policy at the federal state and national levels focuses on financial capital as an integral part of NCP co-production by following the productivity paradigm and encouraging the collaboration between forest actors in forest cooperatives (*Forstbetriebsgemeinschaften*) that organise the joint sales of timber (Chapter III, Pattern 4). The dependence on timber sales as a singular source of income poses a challenge for forest owners as a lack of funding for adapting to changes, e.g., natural disasters or pests, exists (Hernández-Morcillo et al., 2022). Thus, potential financial losses imply jeopardising the provision of other forest NCP. Continuous and goal-oriented financial support is needed to sustain forest multifunctionality and provision of NCP (Hernández-Morcillo et al., 2022). Within this theme, I identified how financial capital is used as an intermediary capital to co-produce and govern material NCP. However, the importance of financial capital for providing other non-monetizable forest NCP should not be neglected.

Theme II: Conservation and collaboration to support regulating NCP

The second theme emphasises the importance of top-down conservation measures and collaborative governance to support the co-production of regulating NCP (Figure 5). Regulating NCP are co-produced locally but affected differently by each governance level. The perspectives demonstrated that co-produced regulating NCP are predominantly governed at sub-national and local levels by various means. The research perspective could show that regulating NCP across ecosystems are mainly governed at the sub-national level via scientific-technical governance that affects physical capital (Chapter II, Cluster 3). Similarly, the policy perspective revealed that regulating forest NCP in the three German case study sites are governed predominantly by the federal state level via the use of incentives in the governing of strategic behaviour (Chapter III, Archetype I). The policy perspective emphasised that scientific-technical governance at the local level is used to steer the use of human and social capital for the co-production of regulating forest NCP (Chapter III, Archetype 6). For example, Natura 2000 management plans influence decisions made in forest management (Winter et al., 2014). Notably, the modes of governance employed at various governance levels correspond to specific anthropogenic capitals available to the respective level. For example, decisions on financial incentives for regulating NCP depend on the availability of budget, while knowledge integration is more easily fostered if collaboration among decision-makers is strong. Similarly, protected areas on the local level support the provision of regulating NCP (Eastwood et al., 2016). Here, the policy and the practice perspective have highlighted a twofold approach within protected areas. For one, protected areas use hierarchical governance by restricting or granting access rights, for example, via zoning, which not only leads to conserving biodiversity but also increases the provision of NCP (Metzger et al., 2020) (Chapter III, Archetype 3; Chapter IV, Pattern 3). The practice perspective demonstrated how protected areas promote collaboration among actors and mediate between differing land-use interests thus strengthening the provision of regulating forest NCP (Chapter IV, Pattern 3). Thereby, protected areas act as "designated coordinator(s)" since they facilitate the collaboration of actors across the region (Bodin, 2017, p. 6). Biosphere reserves, for example, take on a mediator role if they lack the power to enforce conservation measures (Stoll-Kleemann and O'Riordan, 2018). Within this theme, I could demonstrate that various, yet complimentary, governance approaches influence the

co-production of regulating NCP. Comparing the different focal perspectives showed that governance approaches depend on the anthropogenic capitals available to and used for the co-production of regulating NCP.

Theme III: Governing protected areas for non-material NCP

The third theme refers to the importance of protected areas in governing the co-production of non-material NCP (Figure 5). Previous research has shown that protected areas can contribute to increasing non-material NCP delivery (Eastwood et al., 2016). The research perspective linked institutions at regional and local levels, mainly protected areas, to governing non-material NCP hierarchically (Chapter II, Cluster 2). Similarly, and in line with Theme II, the policy perspective revealed that non-material forest NCP are mainly governed by protected areas at the local level in two ways. For one, protected areas contribute to potential non-material NCP by managing habitats and natural spaces in a way that they are attractive to visitors (Chapter III, Archetype 2). However, the extent of this potential depends on the habitats' conservation status (Maes et al., 2012). For example, good natural conditions in Natura 2000 sites are essential when providing opportunities for bird-watching (Kordowska, 2017). Second, infrastructure, such as roads, hiking trails, or visitor centres, facilitates access to protected areas (Schägner et al., 2016) and is governed locally according to the policy perspective (Chapter III, Archetype 5). Despite not revealing a clear pattern, the practice perspective supported this finding as the social network analysis highlighted a local NGO in the Biosphere Reserve Schwäbische Alb to be necessary for the management of hiking trails and thus increasing the potential for non-material NCP (Chapter IV). While recreational infrastructure within biosphere reserves, especially in the buffer zone, was found to contribute to the provision of non-material NCP, no effect of the zoning itself, a form of hierarchical governance, could be found (Palliwoda et al., 2021). Within this theme, I could demonstrate how protected areas increase the potential for non-material NCP by governing natural habitats and the infrastructure needed to realise this potential. In line with existing research, this finding illustrates that protected areas are an essential driver for connecting people with nature.

4.2 Reflections on the research process

Working on this dissertation has revealed four topics that might limit the research presented here but provide opportunities for reflection: i) engaging with practitioners, ii) my own scientific background, iii) conceptual restraints, and iv) operationalisation.

First, my dissertation is partially based on interviews with forest actors in the three case study sites (Chapter IV). Working with practitioners entailed several challenges that influenced the availability of data. My research for this dissertation started in 2020 when the COVID-19 pandemic and the accompanying mobility restrictions reduced people's ability to travel (Bönisch et al., 2020). While my fieldwork took place in 2021, the pandemic still complicated conducting face-to-face interviews and shortened the second fieldwork phase in November due to high COVID-19 case numbers. Some potential respondents were also reluctant to participate due to their employment as public servants. Others, however, described the anonymised interviews as an opportunity to articulate their opinions and the challenges they faced. Thus, research can empower those actors who might feel neglected by higher-level governance processes by giving them a voice (Chambers et al., 2021).

Second, forests and their contributions to people are subject to various conflicts that make their governance challenging (Eckerberg and Sandström, 2013). While my research did not touch upon conflicts per se, many respondents raised various issues linked to conflicting societal demands, forest management perspectives, and governance approaches. My background in environmental social sciences and not in forestry or natural sciences initially posed a challenge when trying to understand the complexities of forest governance. What might supposedly be a disadvantage was beneficial in the interviews. As some forest actors were concerned about being prejudged regarding their management practices, my neutrality encouraged them to speak freely. Interviews may be time and resource-demanding (Shackleton et al., 2021), but inter-, multi- and disciplinary research can adapt principles from transdisciplinary approaches and incorporate hosting open spaces for interviews or focus groups (Chambers et al., 2021).

Third, I referred to a range of frameworks, concepts, and classifications throughout this dissertation, i.e. the IPBES conceptual framework's generalising perspective on NCP (Díaz et al., 2015), the capitals classification by Palomo et al. (2016), and the conceptual governance framework by Primmer et al. (2015). Whilst frameworks in social-ecological research should provide observations regarding causal relationships, their application needs to entail reflections upon their operationalisation "because in a social system the process of research influences the conclusions" (Cumming, 2014, p. 6). Applying the co-production concept may have influenced the findings in this dissertation since referring to human agency as "capitals" or "assets" suggests an instrumental framing and following a notion of commodification, which has been dominant in the discourse on NCP (Anderson et al., 2022). Thus, future research should investigate the role of plural values in the co-production of NCP and their governance and address the role of power in these processes (Arias-Arévalo et al., 2023).

Fourth, methodological gaps in the operationalisation of frameworks and concepts exist (Partelow, 2023). Apart from a few studies (e.g., Bruley et al., 2021; Torralba et al., 2018), the co-production concept lacks operationalisation in NCP and ecosystem services research (Lavorel et al., 2020). Thus, co-production research needs to explore further research methods (Kachler et al., 2023b). Similarly, few studies have applied the governance framework by Primmer et al. (2015) (e.g., Winkler et al., 2021), and quantification of described modes of governance posed a challenge due to their intersecting nature. Hence, additional data collection and analyses could have been beneficial to further dissect the complex interactions contributing to each of these modes of governance, e.g., constellation of actors, power relations, or path dependencies.

4.3 Implications and outlook

4.3.1 Research

The governance of NCP co-production has been studied across ecosystems and in various settings, as shown in Chapter II of this dissertation. However, similar to few studies taking up the co-production concept explicitly (Kachler et al., 2023b), little research has been

conducted on its governance (Chapter II). Thus, this dissertation holds several implications for future research.

For one, Chapters III and IV have shown that gaining a better understanding of governing NCP co-production requires diverse methods. Chapter III employed a policy document analysis to unveil how policy across governance levels intends to govern anthropogenic capitals in the co-production of forest NCP. Nonetheless and in contrast to the ecosystem services concept (Bouwma et al., 2018), the co-production concept has yet to permeate the policy domain. Thus, examining the recognition of the interplay between anthropogenic and natural capitals within policy can only be a first step. Future research is needed to grasp the cross-sectoral and multilevel interplay of policy documents and how they affect practitioners' decisions regarding anthropogenic capitals. This could be done, for example, by studying the horizontal and vertical integration of policies regarding the co-production process (Beland Lindahl et al., 2023). Chapter IV used a social network analysis to map actor relationships in the co-production of forest NCP across the three case study sites. While social network analysis is a standard method for studying forest governance (e.g., García-Amado et al., 2012; Keskitalo et al., 2014; Korhonen et al., 2012; Paletto et al., 2012), this dissertation took a novel approach by investigating actor relationships based on their connection via anthropogenic capitals. However, the research within Chapter IV was solely based on local forest actors' perceptions. Thus, further research needs to expand the sample size and include other stakeholders to understand better how actor ties between governance levels and geographical scales shape the use of anthropogenic capitals in the co-production of forest NCP.

Second, this dissertation has contributed to expanding the thematic focus of research within the *Biodiversity Exploratories* research platform. While previous research focussed on societal actors to better understand stakeholder preferences (Peter et al., 2022) or landscape management decisions (Neyret et al., 2023), Chapters III and IV investigated the broader context by which these decisions and preferences are shaped. Thus, this dissertation can provide a framing on how landscape management decision-making in the

three case study sites is embedded in Europe and Germany's multi-level governance systems.

Finally, eight gaps and challenges for future research were identified in Chapter V of this dissertation: 1) expanding the spatio-temporal scope of case study sites to inform territorial planning, 2) addressing conceptual gaps, 3) accounting for the diversity of stakeholders, 4) understanding the polycentric nature of governing anthropogenic capitals in NCP co-production, 5) dealing with conflicts and power asymmetries, 6) evidence-based and collaborative approaches to global changes, 7) plural values in governing anthropogenic capitals, and 8) identifying leverage points for sustainable NCP co-production. Addressing these challenges would not only lead to a more holistic understanding of the complex decision-making processes that affect the use of anthropogenic capitals in NCP co-production but also equip decision-makers with an evidence base to foster sustainable forms of NCP co-production.

4.3.2 Policy and practice

Forest governance and management face multiple challenges regarding the sustainable supply of forest NCP (Hernández-Morcillo et al., 2022). Solutions to these challenges largely correspond to the use of anthropogenic capitals in the co-production of forest NCP. Thus, the findings of this dissertation have two implications for policy and practice.

First, policymakers can use this dissertation's findings to understand better how policy drives the use of specific anthropogenic capitals and may thus favour particular NCP over others. For example, Chapter III revealed that policy documents across governance levels predominantly refer to human and social capitals in the co-production of material and some regulating forest NCP. Governance related to these NCP and capitals was mainly hierarchical and scientific-technical. While the imbalance towards specific NCP and capitals may not reflect societal demands towards forests or the solutions needed for the challenges described by Hernández-Morcillo et al. (2022), Archetypes 2 and 5 identified by in Chapter

III display pathways how policy can support the supply of non-material NCP by fostering synergies with regulating NCP in forests.

Second, due to their dependence and sustained focus on timber sales as a main source of income, it remains difficult for practitioners to fully integrate the supply of regulating and non-material NCP into their management strategies without government support (Mann et al., 2022). Chapters III and IV illustrate how financial capital is used as a means to an end when co-producing marketable and non-monetizable NCP. Practitioners can draw on these findings to build an argument for increasing and sustaining financial payments that favour regulating and non-material NCP over forest productivity.

5. Conclusions

This dissertation contributes to the emerging research field on the co-production of nature's contributions to people (NCP) by investigating how multi-modal and multi-level governance influences the use of anthropogenic capitals to provide NCP. Focussing on forests in three case study sites across Germany and approaching the topic through the focal perspectives, research, policy, and practice has led to identifying three broad themes characterising the governance of NCP co-production. For one, financial capital is used to govern the co-production of material NCP, namely timber. Second, conservation and collaboration support the provision of regulating NCP by drawing on human, social, financial, and physical capital. Third, protected areas increase the potential for obtaining non-material NCP by governing infrastructure and habitats. By better understanding how governance shapes the interplay between anthropogenic and natural capitals, this dissertation contributes to identifying governance arrangements for the sustainable co-production of NCP. Thus, this dissertation provides insights and implications for the pressing social-ecological challenges connected to varying societal demands for NCP in forests and beyond.

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Chapter II

Governance to manage the complexity of nature's contributions to people co-production

Roman Isaac, Jana Kachler, Klara J. Winkler, Eerika Albrecht, María R. Felipe-Lucia, Berta Martín-López

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CHAPTER TEN

Governance to manage the complexity of nature's contributions to people co-production

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Abstract

Nature's contributions to people (NCP) support people's quality of life and are generated by an interplay of both natural and anthropogenic capitals, known as NCP co-production, which also includes ecosystem services. A governance system of formal and informal institutions on different yet interlinked spatial, administrative, and temporal scales influences the management of these capitals underpinning the co-production of NCP. While the field of NCP governance is well established, the role of governance on natural and anthropogenic capitals in NCP co-production is under-researched, which might undermine its integration into decision-making. Here, we analyse how governance of anthropogenic capitals influencing NCP co-production has been researched in the scientific literature. We conducted two systematic literature reviews of publications on ecosystem service governance and ecosystem service and NCP co-production. We distinguish different modes of governance directed at NCP co-production following the classification described by Primmer et al. (2015)—hierarchical, scientific-technical, (adaptive)-collaborative governance and the governing of strategic behaviour. These governance modes resemble the pluralism in ecosystem services governance as they involve various actors and governance approaches. We tie these governance modes to the anthropogenic capitals (human, social, physical, or financial) involved in NCP co-production at the respective administrative, spatial, and temporal scales. Our results show that the literature refers to a variety of combinations of governance modes and anthropogenic capitals involved in NCP co-production. Anthropogenic capitals are mostly studied in multiple governance modes, with material NCP being the most commonly NCP investigated. Our results highlight a major research gap in the NCP co-production literature, which currently neglects the role of governance when assessing the interplay of anthropogenic and natural capitals.

1. Introduction

Within its conceptual framework, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) explicitly recognises the possibility of achieving a good quality of life through the access to nature's contributions to people (NCP), which do not only depend on the state and functioning of natural elements but also on anthropogenic assets or capitals (Díaz et al., 2015). This idea was formerly conceived in the ecosystem services literature with the concept of ecosystem services co-production (Palomo et al., 2016). Lavorel et al. (2020) define co-produced NCP as "the benefits [provided] from nature to people through multiple, long-term and dynamic socio-ecological interactions and the

associated interplay of natural and human-derived capitals" (p.3). Recent research has assessed the contributions of anthropogenic capitals to the provision of ecosystem services and NCP (see, e.g. Bruley et al., 2021; Fischer and Eastwood, 2016; Gómez-Baggethun et al., 2013; Lavorel et al., 2020; Palliwoda et al., 2021; Raymond et al., 2010; Torralba et al., 2018). For example, Lavorel et al. (2020) highlight that a lack of operationalisation regarding the co-production concept exists and apply it to the case of climate change adaptation across several study sites. Bruley et al. (2021) conducted a comprehensive study on NCP co-production in a multifunctional landscape in the French Alps, concluding that governance, which might also be conceptualised as social capital, is relevant for the co-production of NCP.

In addition, the IPBES conceptual framework accentuates the reciprocal relationships between institutions and governance with NCP, anthropogenic assets, and ultimately people's quality of life (Díaz et al., 2015). In fact, the IPBES conceptual framework places institutions at its core to emphasise their key role in mediating the provision of NCP as well as the access and control over NCP (Díaz et al., 2015; Martín-López et al., 2019). Governance, however, goes beyond the role of institutions. Thus, this review follows a framework proposed by Primmer et al. (2015) who differentiate between hierarchical governance—which includes institutions—, scientific-technical governance, (adaptive)-collaborative governance, and the governing of strategic behaviour. These diverse modes of governance not only reflect the plurality of governing ecosystem services, but the plurality of actors involved in this governance. While hierarchical governance is predominantly based on formal institutions, for example in form of national legislation, (adaptive) collaborative and scientific-technical governance is based on involving various non-state actors due to their expertise and stakes in governing ecosystem functions and services (Primmer et al., 2015). Méndez et al. (in this special issue) aim to understand when the pluralism of actors and governance modes is limited in achieving its goals and explore how strengthening pluralism can contribute to more sustainable trajectories.

While research on ecosystem services has increased exponentially over the last two decades (Droste et al., 2018), ecosystem services governance research has not grown correspondingly (Winkler et al., 2021). Nonetheless, ecosystem services governance has gained increasing attention in the science-policy interface over the last years and is now an established field of research (Sattler et al., 2018). Despite this, few empirical studies refer explicitly to the involvement of governance in the co-production of NCP (see e.g. Auer et al., 2017; Lavorel et al., 2019, 2020; Vialatte et al., 2019). In fact, to our

best knowledge, no paper has attempted to review the research status of governance of NCP co-production.

This paper aims to analyse how previous literature on NCP co-production has addressed the different modes of governance proposed by Primmer et al. (2015) and how they are directed at anthropogenic capitals involved in the co-production of NCP. To do so, we conduct a systematic literature review that aims to: (i) show which NCP are studied by research conducted on ecosystem services governance and NCP co-production; (ii) acknowledge the anthropogenic capitals contributing to these NCP; and (iii) identify which modes of governance or combinations of these are directed at anthropogenic capitals involved in the co-production of NCP studied in the literature. Our work builds a bridge between the debate on NCP and ecosystem services governance and the debate focussing on the interplay of natural and anthropogenic capitals in NCP co-production. While the first debate has evolved around the question of how governance and institutions can affect ecosystem services and the way people use and manage them (see e.g. Winkler et al., 2021), the latter debate seeks to understand how humans contribute to the supply of NCP and ecosystem services through the use of different anthropogenic capitals (see e.g. Bruley et al., 2021; Lavorel et al., 2019; Palomo et al., 2016). Thereby, we contribute to a better understanding of how anthropogenic capitals in NCP co-production are governed and lay the foundation for further research to analyse which modes of governance ensure the co-production and use of NCP in a sustainable manner.

2. Theoretical background

2.1 Nature's contributions to people and their co-production

NCP encompass all "contributions, both positive and negative, of living nature (i.e., biodiversity of organisms, ecosystems, and their associated ecological and evolutionary process) to quality of life for people" (Díaz et al., 2018, p. 3). The NCP concept includes two analytical perspectives: a context-specific and a generalising perspective. The context-specific perspective embraces the diversity in perceptions on NCP around the world, highlighting that the same NCP can be perceived differently depending on the personal context. The generalising perspective seeks to provide a context-independent definition for 18 NCP that underpin people's quality

of life (Hill et al., 2021). The 18 NCP are classified into three groups: material, regulating and non-material NCP (Díaz et al., 2018).

Unlike the common ecosystem services classifications of provisioning, regulating, and cultural services, the NCP concept acknowledges that the cultural dimension diffuses through all NCP instead of being confined into a single group (Kadykalo et al., 2019). Material NCP include all "physical substances, objects, or materials from nature which people use to consume to live," such as providing of food or building materials (Hill et al., 2021, p. 911). Regulating NCP refer to the way ecosystems "modify environmental conditions experienced by people, and/or sustain and/or regulate the generation of material and non-material contributions" (Díaz et al., 2018, p. 5) like the regulation of freshwater and air quality or the pollination of plants. Last, non-material NCP entail "nature's effects on subjective or psychological aspects underpinning people's quality of life" on both an individual and societal level (Hill et al., 2021, p. 911). This includes the ways nature benefits humans by providing "physical and psychological experiences," "learning and inspiration" and "supporting identities" (Díaz et al., 2018). In this paper, we use the categories of material, non-material and regulating NCP portrayed by the generalising perspective with the aim to have a universal system of classification that aligns with former research on ecosystem services.

While the IPBES conceptual framework highlights that NCP are co-produced by nature and humans through the use of anthropogenic assets (Díaz et al., 2015, 2018), the debate on ecosystem services has long regarded them as a "free gift" solely provided by nature (Spangenberg et al., 2014, p. 40). However, recent literature has considered the dual nature of ecosystem services as being provided by contributions from nature and anthropogenic capitals (see e.g. Bruley et al., 2021; Fischer and Eastwood, 2016; Lavorel et al., 2020; Palomo et al., 2016; Raymond et al., 2010).

In this paper, we use the NCP concept because it is a broader paradigm that encompasses not only the ecosystem services framework but also the multiple ways by which societies relate with nature and contribute different anthropogenic assets to the provision of NCP (see Díaz et al., 2018; Hill et al., 2021). Over the last decade, diverse framings of co-production have evolved in ecosystem services and NCP research. Lele et al. (2013) first noted that co-production involves ecosystem functions and different forms of human agency, technologies, and financial capital. Spangenberg et al. (2014) described how human agency shapes the co-production of ecosystem services later in more detail. Palomo et al. (2016) built on the definition of capitals given by Goodwin (2003) to specify how human, social, physical

BOX 1 Definitions of the anthropogenic capitals involved in NCP co-production.

Human capital refers to people's capabilities, including health, informal knowledge, formal knowledge, skills, motivation, and labour, that can yield a flow of NCP.

Social capital includes all intangible assets associated with interactions between people, including formal and informal networks, trust, and formal and informal institutions required for enhancing the flow of NCP.

Physical capital refers to technological or manufactured assets that contribute to the NCP flow.

Financial capital Virtual mechanisms in the form of savings, credits, and other monetary forms are used for trading, maintaining, or enhancing natural, human, social or physical capitals that contribute to the flow of NCP.

Adapted from Isaac, R., Kachler, J., Martín-López, B., Felipe-Lucia, M.R., 2022. Fieldwork Protocol Effects of land management on the Supply and Distribution of ecosystem services (ESuDis). https://doi.org/10.13140/RG.2.2.24291.84006: S1 and based on 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, in: Advances in Ecological Research. Elsevier, pp. 245–283. https://doi.org/10.1016/bs.aecr.2015.09.003 and Goodwin, N.R., 2003. Five Kinds of Capital: Useful Concepts for Sustainable Development.

and financial capitals interact with natural capital to provide ecosystem services. In this paper, we use the classification of human, social, physical and financial capitals involved in co-production as explained by Palomo et al. (2016) to determine which capitals are the target of management and governance actions. Box 1 provides a definition of the four types of capitals.

2.2 Governance of nature's contributions to people

Within the IPBES conceptual framework, governance and institutions play an integral role and affect NCP by regulating the access to, control over, and allocation of capitals contributing to the co-production of NCP (Díaz et al., 2015). Ecosystem services governance "refers to the processes by which a range of actors (e.g. government, resource users, environmental groups and private entities) make decisions that influence the use of ecosystem-derived goods and services" (Metzger et al., 2020, p. 2). With the emergence of research on ecosystem services governance, many concepts from the general governance literature have been introduced to the ecosystem service literature. Despite the increased attention on governance in ecosystem services

research, Sattler et al. (2018) suggest that ecosystem services literature has only partly succeeded in researching the full complexity of ecosystem services governance.

In an attempt to navigate the genuine complexity of governance, a variety of frameworks have been developed to analyse ecosystem services governance across administrative and spatial scales, beneficiaries, and ecosystems (see e.g. Albert et al., 2017; Fischer and Eastwood, 2016; Knüppe and Pahl-Wostl, 2011; Metzger et al., 2020; Primmer et al., 2015; Vialatte et al., 2019). In some frameworks, the analysis of ecosystem services governance can be specific to a particular ecosystem or set of services. For example, Knüppe and Pahl-Wostl (2011) assess the governance of groundwater to enable scholars to improve their understanding of groundwater-related ecosystem services. Fossey et al. (2020) assess the governance related to soil ecosystem services and how these are integrated into policy-making in the form of land-use planning. Vialatte et al. (2019) assess the multiple ecosystem services provided in agricultural landscapes by considering social and ecological components and the effects of multi-level governance.

To provide a tool for the empirical assessment of ecosystem services governance, Primmer et al. (2015) present a more universal framework that highlights how decision-making actively shapes ecosystems and their services. The framework distinguishes between four modes of governance: scientific-technical, (adaptive) collaborative, hierarchical governance, and the governing of strategic behaviour. Box 2 explains each of the governance modes in detail. The strength of this framework lies in the possibility of applying it across governance scales and in a range of ecosystem contexts. Winkler et al. (2021) applied this framework to understand how ecosystem service research has addressed governance, finding that hierarchical governance is the most prominently studied ecosystem service governance mode and often affects the three other governance modes.

In this manuscript, we apply the framework by Primmer et al. (2015) to the literature on NCP co-production and investigate whether the findings by Winkler et al. (2021) can be confirmed for the governance of capitals in NCP co-production. Building on the findings of Winkler et al. (2021), we differentiate between adaptive and collaborative governance to gain a more nuanced view of how governance has been used in the literature on NCP co-production (see Box 2). Using the framework by Primmer et al. (2015), Box 3 illustrates how governance of the different anthropogenic capitals matters for NCP co-production in an exemplary farming system.

BOX 2 Modes of nature's contributions to people (NCP) governance.

Hierarchical governance concerns regulations that influence NCP and the other modes of governance (Primmer et al., 2015). In contrast to collaborative governance, hierarchical governance is executed by state actors through formal institutions. Formal institutions exist mainly in the form of policies (e.g. frameworks, laws, regulations) that directly affect NCP or the other governance modes. As interdependencies between policies across governance levels exist, hierarchical governance is often studied in multi-level contexts. Therefore, governance of NCP is often linked to scale mismatches (Borgström et al., 2006; Winkler et al., 2021). Scale mismatches occur when ecosystem boundaries do not match with the administrative units' borders. A positive example is the Water Framework Directive, the first European Union directive using a natural unit (water catchments) for governance, rather than administrative units such as counties (Moss, 2012).

Scientific-technical governance refers to decision-making based on scientific and technical arguments (Primmer et al., 2015). Experts, who are not necessarily scientists influence decision-making, play a vital role in this process. The underlying expectation for scientific-technical governance is that effective dissemination of scientific knowledge leads to better governance (Huth and Possingham, 2011; Sutherland et al., 2004). Land-use planning serves as an example for this governance mode as it incorporates scientific arguments when making decisions about potential trade-offs between NCP (Paavola and Hubacek, 2013).

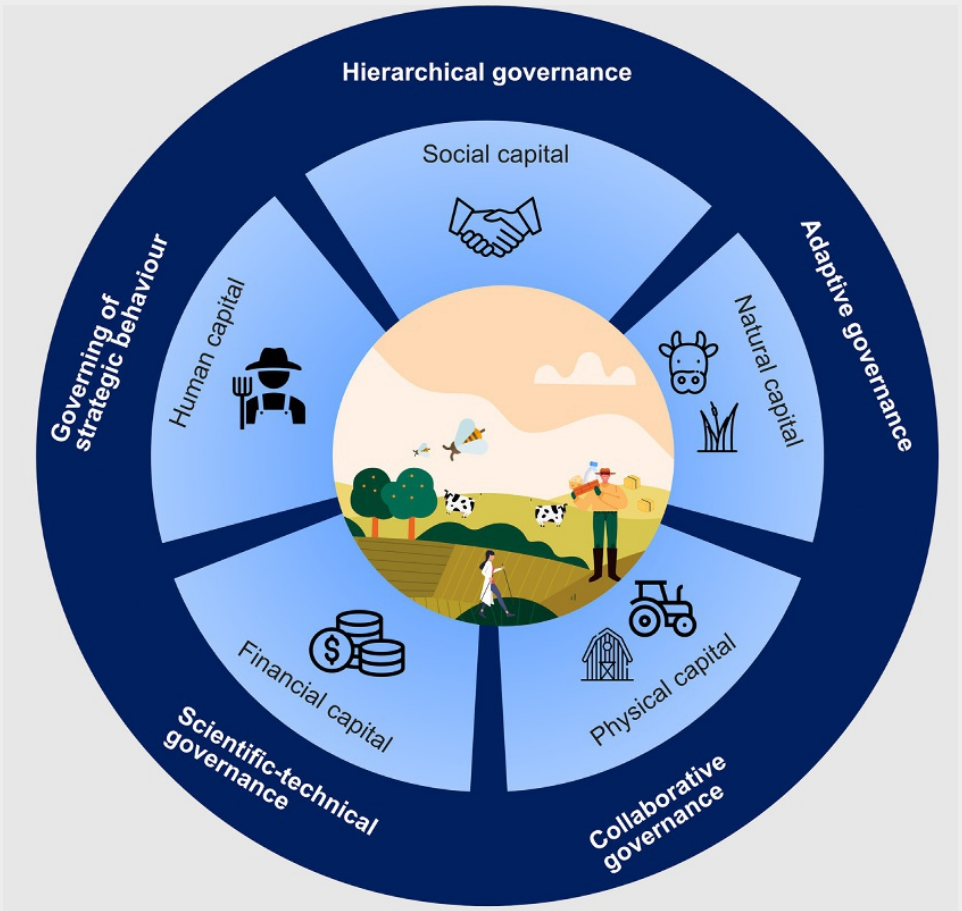
Collaborative governance stresses the importance of collective learning and bottom-up participatory processes that embrace diverse stakeholder perspectives (Primmer et al., 2015). Moreover, collaborative governance is best executed when based on open and transparent processes to collective problem-solving (Newig and Fritsch, 2009). Participatory processes are often considered to contribute positively to ecological outcomes (Bäckstrand et al., 2010).

Adaptive governance tries to increase the responsive capacity to changing circumstances, including changing societal values (Burkhard et al., 2012). Examples are stewardships approaches to ecosystems (Chapin III et al., 2015; Olsson et al., 2008) or approaches that promote local learning (Cork et al., 2006).

Governing of strategic behaviour features the potential of governance arrangements and the interactions between them to be transformative (Primmer et al., 2015). It refers to market-based or commercial approaches. This implies the aim to influence policy-making processes through lobbying with the goal of affecting policies and protecting certain interests (Newig and Fritsch, 2009; Primmer et al., 2015). Besides, governing of strategic behaviour can nudge behaviour in a wanted direction (Primmer, 2011). Payments for ecosystem services are a typical example of governing strategic behaviour often referred to in the literature (see e.g. Börner et al., 2010; Rival, 2010; Van Hecken and Bastiaensen, 2010).

BOX 3 Governance modes affecting capitals in nature's contributions to people (NCP) co-production.

To illustrate how governance affects NCP and the co-production underpinning NCP, we use a fictional farm with grass-fed dairy cows as an example. The various NCP arising at the farm level and the capitals contribution to them as well as the different forms of governance affecting these are described below.



Graphic by Annika R. Schmidt.

3. Methods

3.1 Data collection

We conducted a systematic literature review (Bryman, 2012) to understand how different modes of governance are directed at capitals in NCP co-production. Since co-production of NCP is a relatively new concept, we assumed that little research could be found by only searching for publications on the governance of anthropogenic capitals in NCP co-production. Thus, we combined the results of two searches. The first focuses on publications on ecosystem services and NCP co-production. The second was conducted by Winkler et al. (2021) and deals with ecosystem services governance. Thus, we approached the governance of anthropogenic capitals in NCP co-production from two vantage points. In both cases, we only included articles that were peer-reviewed and written in English.

The first search on NCP and ecosystem services co-production was conducted to capture literature on ecosystem services and natural and anthropogenic capitals in their co-production in an unlimited to 2020 timespan. The search was automatically confined to the years 1945 to 2020 by the *Web of Science*. The search string employed included *'ecosystem services*'* as well as other synonyms (e.g. *'ecosystem good*'*, *'ecosystem function*'*, *'nature benefit*'*, *'provisioning service*'*, *'regulating service*'*, *'natures contribution* to people'*, *'supply*'*, *'demand*'* ,*'use*'*, *'co-production*'*, *'co-creation*'*), as well as different forms of *'anthropogenic capital'* (e.g. *'human capital*'*, *'human asset*'*, *'soci* capital*'*, *'soci* factor*'*, *'soci* asset*'*, *'technological capital*'*, *'manufactured capital*'*, *'financial capital*'*, *' physical capital*'*). For the entire search string see Supplementary material S1 in the online version at https://doi.org/10.1016/bs.aecr.2022.04.009. Based on this search string, the literature search returned 384 publications. For the literature assessment we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al., 2021). Assessing the abstracts resulted in 170 papers that potentially included NCP co-production. A full-text analysis of these publications resulted in 25 publications that explicitly (i.e. stated by authors) or implicitly (i.e. not stated by authors but covered in the paper) referred to NCP co-production and were included in the full-text coding (see Supplementary material S2 in the online version at https://doi.org/10.1016/bs.aecr.2022.04.009 for the PRISMA flow diagram).

The second search by Winkler et al. (2021) on ecosystem services governance used a search string with the words *'ecosystem service* and*

'governance.' The search was limited to the years 2006 to 2019, and the year 2020 was added for this review, to capture literature on ecosystem services and governance after the Millenium Ecosystem Assesment's publication (Millennium Ecosystem Assessment (Program), 2005). The selection of publications that had on average at least one citation per year since their publication was a criterion for relevance in the scientific discourse. The selection criteria yielded 157 publications that focused on ecosystem services and governance and were empirical or had an empirical component. Empirical in this case refers to research based on observation and measurement of phenomena. Next, we screened the abstracts and, if uncertain, the full text to see whether the publications explicitly or implicitly dealt with NCP co-production. The application of this final selection criterion resulted in 21 publications on ecosystem services governance which referred to NCP co-production.

After removing one duplicate found in both searches, 45 publications were fully coded (see Supplementary material S3 in the online version at https://doi.org/10.1016/bs.aecr.2022.04.009 for the list of publications reviewed). We followed a deductive code system based on the governance framework proposed by Primmer et al. (2015) and the co-production framework by Palomo et al. (2016). Besides general characteristics for each publication (i.e. the year of publication, location, temporal scale, spatial scale, landscape type, data source and methods for data collection and analysis), we coded information concerning the type of NCP co-production (i.e. explicit or implicit), the different NCP categories (based on Díaz et al., 2018), the anthropogenic capitals involved in NCP co-production (based on Palomo et al., 2016), information about the governance of NCP co-production (i.e., governance level, polycentric governance, governance affecting capitals or NCP, formal governance, informal governance (for definitions please see Supplementary material S4 in the online version at https://doi.org/10.1016/bs.aecr.2022.04.009), and governance modes (based on Primmer et al., 2015). Supplementary material S4 in the online version at https://doi.org/10.1016/bs.aecr.2022.04.009 provides a complete list of the variables used in the analysis, including definitions and references when relevant.

A clear distinction between social capital and governance is difficult to make throughout the literature on NCP co-production given that social capital encompasses formal and informal institutions (see Box 1). We, therefore, counted the involvement of institutions in NCP co-production as both social capital and governance.

3.2 Data analysis

We employed descriptive statistics to determine which anthropogenic capitals were involved in the co-production of the 18 NCP categories and the respective NCP groups and tied these to the governance modes. To see which combinations of governance modes, anthropogenic capitals and NCP groups were referred to most often we counted and ranked the combinations. Finally, to explore the relations between NCP categories, anthropogenic capitals, and governance modes, we conducted a Hierarchical Cluster Analysis (HCA) with the factors obtained in a Multiple Correspondence Analysis (MCA) using *XLSTAT* Version 2020.3.1.2. The MCA was run with the NCP categories, anthropogenic capitals, and governance modes. We also displayed the centroids of governance levels and informal institutions to gain in-depth knowledge of those connections.

4. Results

4.1 General characteristics of publications and geographic distribution of case studies

The number of publications on the governance of NCP co-production reviewed for this paper amounts to 45 publications. Most publications referred to at least one empirical method involving stakeholders (Fig. 1A). Regarding all methods, more than half of the publications used two or more methods (56%; $n = 25$). We found that interviews ($n = 29$) and surveys ($n = 17$) were conducted most often in the reviewed publications. Literature reviews ($n = 11$) were only conducted in combination with other methods and as a way to determine research gaps. Moreover, a range of other methods, including observation ($n = 7$), ecological data collection ($n = 6$) as well as workshops ($n = 4$), and focus groups (n = 4) were used.

We found that more than half of the publications included case studies on the regional level (62%, $n = 28$) (Fig. 1B). The regional level, in this case, describes an entity larger than a village or city (local level), but smaller than the sub-national level (e.g. states, departments). Examples for the regional level are shires, districts, or counties. Only 13 case studies (29%) looked at NCP co-production on the local level, which refers to a municipality, village, or city. Two case studies conducted research at higher administrative levels. Gatzweiler (2006) referred to a case study on the national level, namely Ethiopia, while Hicks and Cinner (2014) took a multi-national approach when comparing case studies from Kenya,

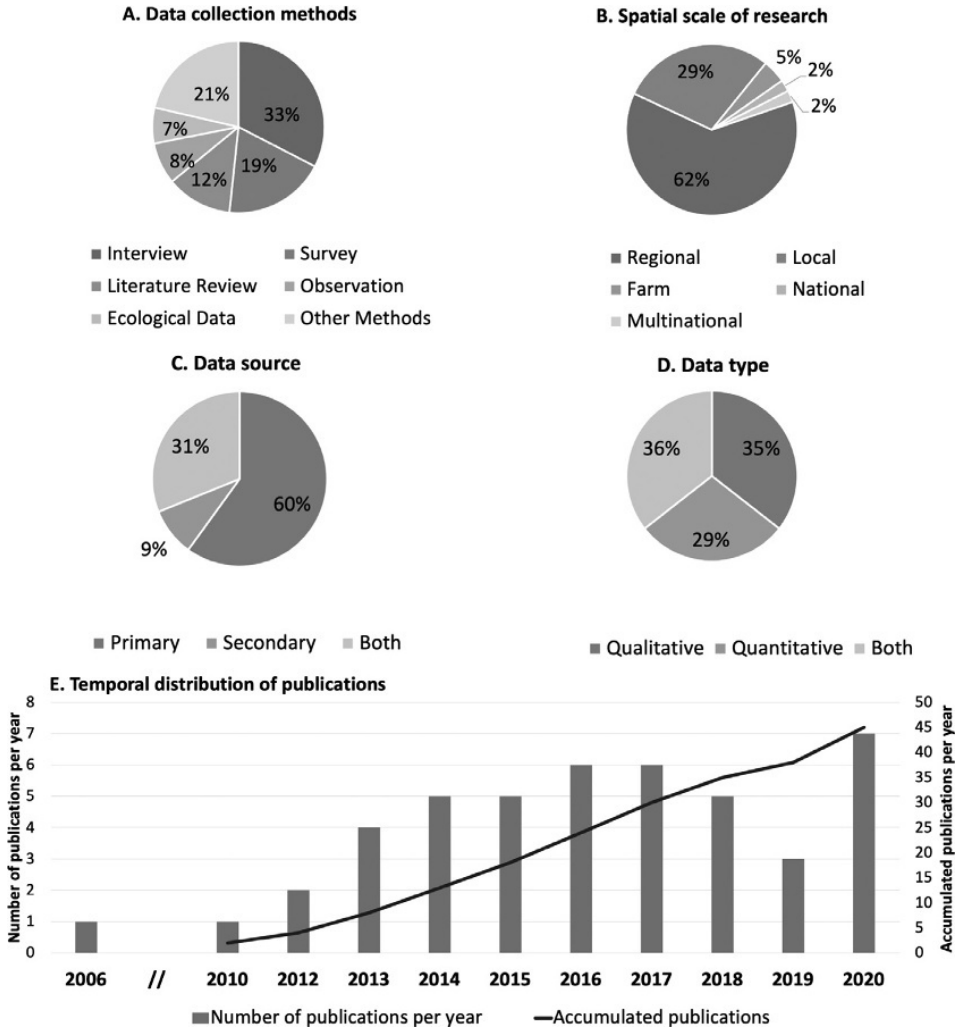


Fig. 1 Distribution of papers on the governance of NCP co-production based on: (A) data collection methods employed (*other methods* include workshops and focus groups), (B) spatial scale at which the research was conducted, (C) source of data, (D) type of data used in publications and (E) temporal distribution of reviewed publications between 2006 and 2020.

Madagascar, Seychelles, and Tanzania. The data used in the reviewed publications were predominantly primary (60%, $n = 27$) (Fig. 1C). Some studies used primary as well as secondary data (31%, $n = 14$), for example interviews paired with a literature review (e.g. Knüppe et al., 2016). Only 9% used secondary data, which had come from previously conducted case studies ($n = 4$). Most publications used qualitative (36%, $n = 16$) and a mixture of both types of data (36%, $n = 16$). Only 13 publications (28%) used quantitative data (Fig. 1D). We do not see a clear trend with regards to the number of publications per year (Fig. 1E).

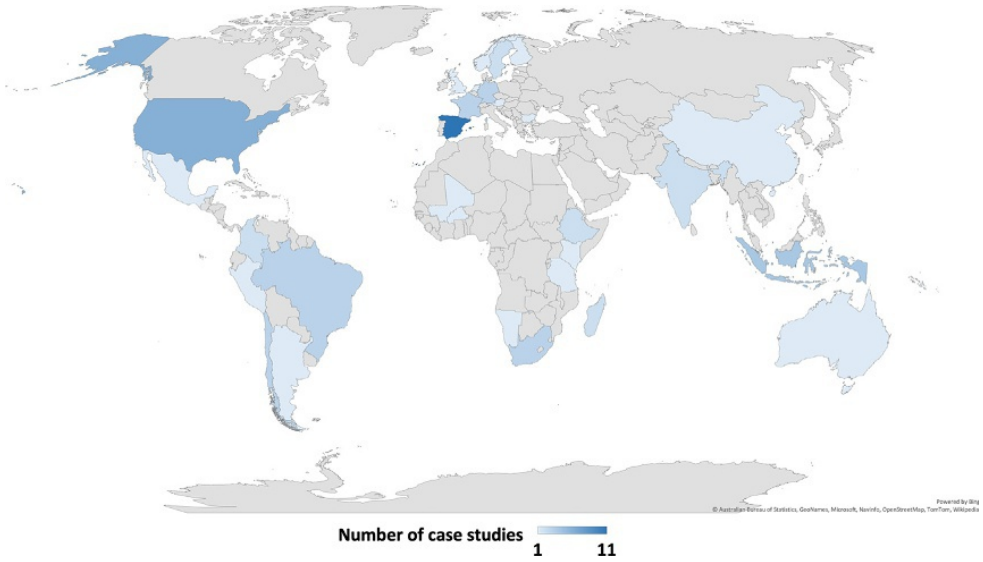


Fig. 2 Geographic distribution of publications on governance and NCP co-production.

Most case studies were located in Spain ($n = 11$) followed by the United States ($n = 6$) and France ($n = 4$) (Fig. 2). Regarding continents, most case studies were placed in Europe (39%, $n = 26$) followed by Africa (22%, $n = 14$), South America (15%, $n = 10$) and North America (12%, $n = 8$). The least case studies were conducted in Asia (9%, $n = 6$) and Oceania (3%, $n = 2$).

4.2 Anthropogenic capitals in nature's contributions to people co-production

Out of the 45 publications dealing with NCP co-production, only nine (20%) highlight explicit co-production, while 36 (80%) deal with NCP co-production implicitly. Hence, the interplay of natural and anthropogenic capitals in the provision of NCP is recognised by many authors but not defined as NCP co-production. Besides, nine publications (20%) do not refer to any form of governance when studying the co-production of NCP. Thus, no data from these publications can be found in the following.

4.2.1 General findings

We identified a total of 185 co-produced NCP, which are studied with one or more modes of governance. Material NCP are described most often (34%, $n = 62$) in the context of NCP co-production, followed by regulating NCP second most (28%, $n = 51$) and non-material NCP (19%, $n = 36$). A fifth (19%) of interactions between natural and anthropogenic capitals found

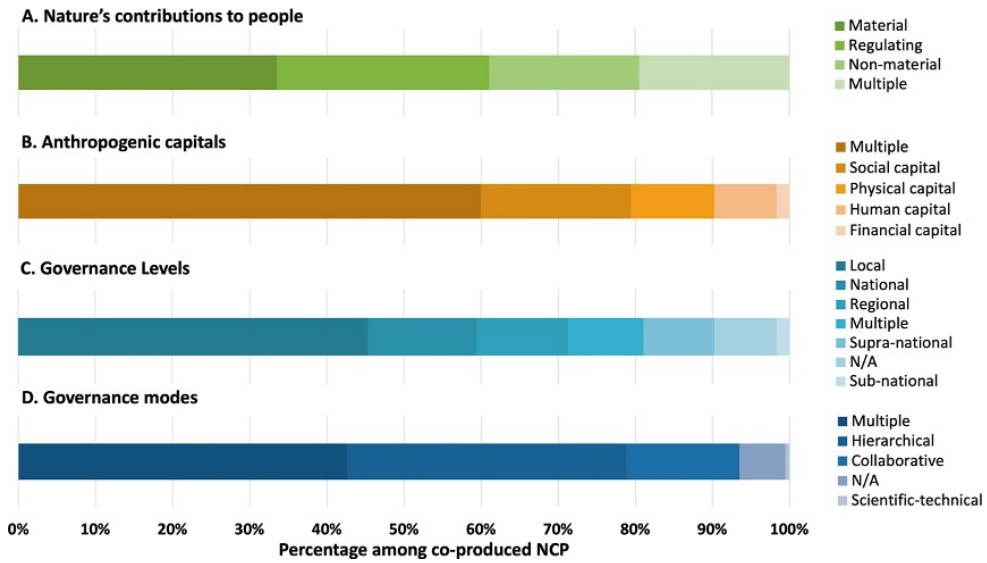


Fig. 3 Percentage of publications referring to the three groups of Nature Contributions to People (NCP), anthropogenic capitals, different governance levels and modes of governance relating to NCP co-production. Some publications did not refer to governance levels and modes and are marked as N/A (Not Applicable).

in the literature cannot be tied to one single NCP but resulted in the co-production of multiple NCP ($n = 36$) (Fig. 3A).

More than half of the NCP are co-produced by natural capital and multiple anthropogenic capitals (60%, $n = 111$). Co-production of NCP only involving one capital type is based on social capital (19%, $n = 36$), physical capital (11%, $n = 20$), human capital (8%, $n = 15$) and financial capital ($n = 3$, 2%) (Fig. 3B). As natural capital is always involved in the co-production of NCP it is not listed in this review.

We found that co-production of NCP is studied at various governance levels. Almost half (45%, $n = 84$) of co-produced NCP are studied with governance on the local level and 14% at the national level (n = 26). The regional (12%, $n = 22$), supra-national (9%, $n = 17$) and sub-national (2%, $n = 3$) levels play a subordinate role in the governance of NCP co-production. A tenth of co-produced NCP are affected by multi-level governance (10%, $n = 18$) while 8% are not related to any specific level ($n = 15$) and are represented as N/A (Fig. 3C). For example, local governance is studied by Malinga et al. (2018) who compare NCP in large scale and smallholder farms in South Africa, while Lavorel et al. (2020) focus on the regional level when researching climate adaptation services in the French Alps.

Besides, our review shows that NCP co-production is mostly influenced by combinations of multiple modes of governance (43%, $n = 79$). While hierarchical governance affects 36% of co-produced NCP ($n = 67$), collaborative governance is only linked to 15% ($n = 27$) and scientific-technical governance to only one co-produced NCP (1%). Adaptive governance and the governing of strategic behaviour are only studied in combination with other governance forms and are not studied by themselves. Some co-produced NCP cannot be connected to a specific mode of governance and are labelled as N/A (6%, $n = 11$) (Fig. 3D).

4.2.2 Material NCP

Out of the 62 material NCP we found that food and feed is the most studied at 79%. While materials make up 8% of material NCP, energy, and other material NCP only account for 7% and 6%, respectively (Fig. 4A). Formal institutions are the principal anthropogenic capital involved in the co-production of material NCP with 29%. Infrastructure and built capital play an important role as they are linked to 17% of material NCP. Networks (10%), informal knowledge (10%), formal knowledge (8%) and tools and machinery (8%) play a subordinate role in the co-production of material NCP. Financial capital is mostly studied in combination with other capitals and is therefore not referred to on its own in the following (Fig. 5A).

4.2.3 Regulating NCP

Of the 51 regulating NCP we found, freshwater quality (21%), soils and sediments (19%), and freshwater quantity are the most studied. Pollination (14%) and climate (8%) are studied less often. All other regulating NCP make up 20% of this group (Fig. 4B). Formal knowledge and tools and machinery contribute most to the co-production of regulating NCP at 16% each. Networks and other human capitals play a subordinate role at 14% each (Fig. 5B).

4.2.4 Non-material NCP

Psychological and physical experience (61%) are the most studied of the 36 non-material NCP we found. Supporting identities (11%), learning and inspiration (8%) and all other non-material NCP (20%) only account for 39% (Fig. 4C). Non-material NCP are mainly co-produced by informal (34%) and formal institutions (21%) as well as infrastructure and built capital (26%). All other anthropogenic capitals contribute 19% (Fig. 5C).

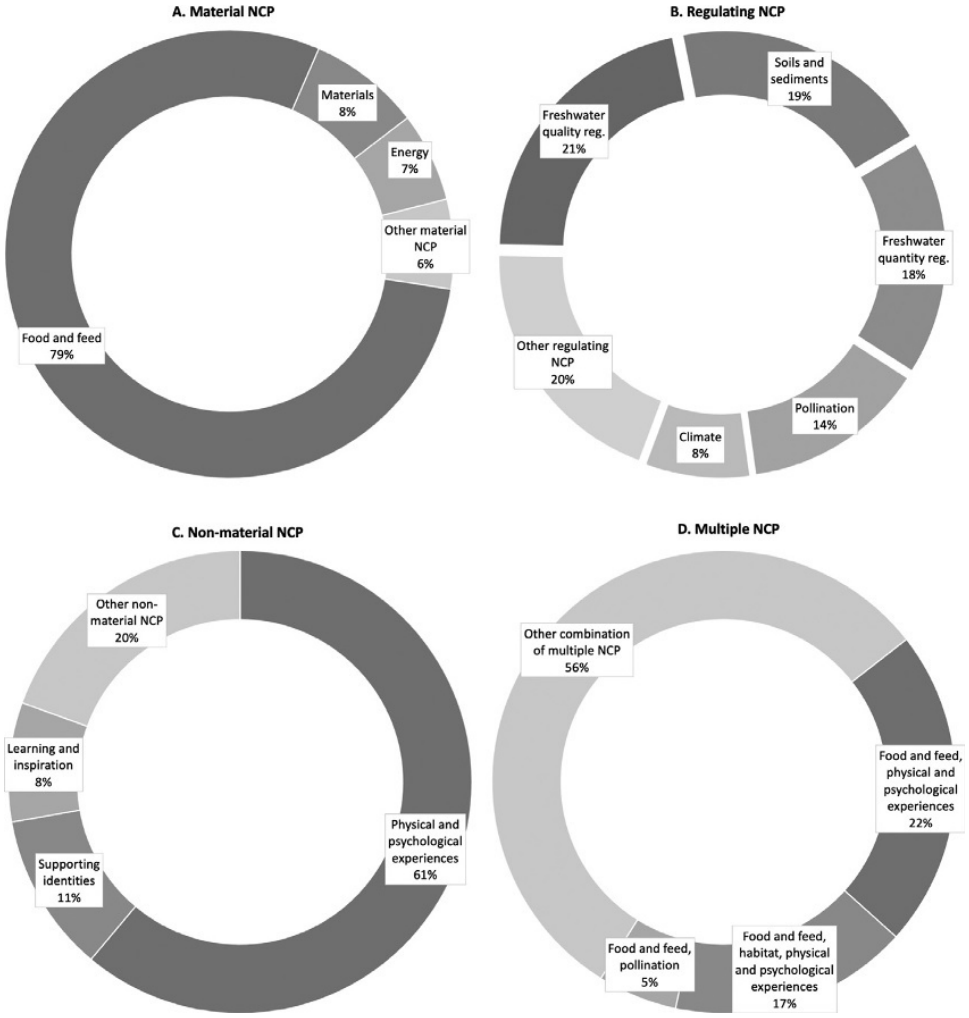


Fig. 4 Nature's contributions to people (NCP) sorted by their group (Abbreviation: reg. = regulation).

4.2.5 Multiple NCP

Within our review, we found 36 combinations of multiple NCP studied together. The material NCP food and feed was most often studied with the non-material NCP psychological and physical experiences. Together they make up 22% of NCP studied in combination. The second-most found combination of multiple NCP includes food and feed, habitat, and psychological and physical experiences (17%), followed by food and feed and pollination (5%). All other combinations of multiple NCP amount to 56% (Fig. 4D). Formal institutions contribute most to the co-production of multiple NCP (28%). Infrastructure and built capital are second (16%) and other human capitals, which include capitals not captured by our human capital definition, come third (15%) (Fig. 5D).

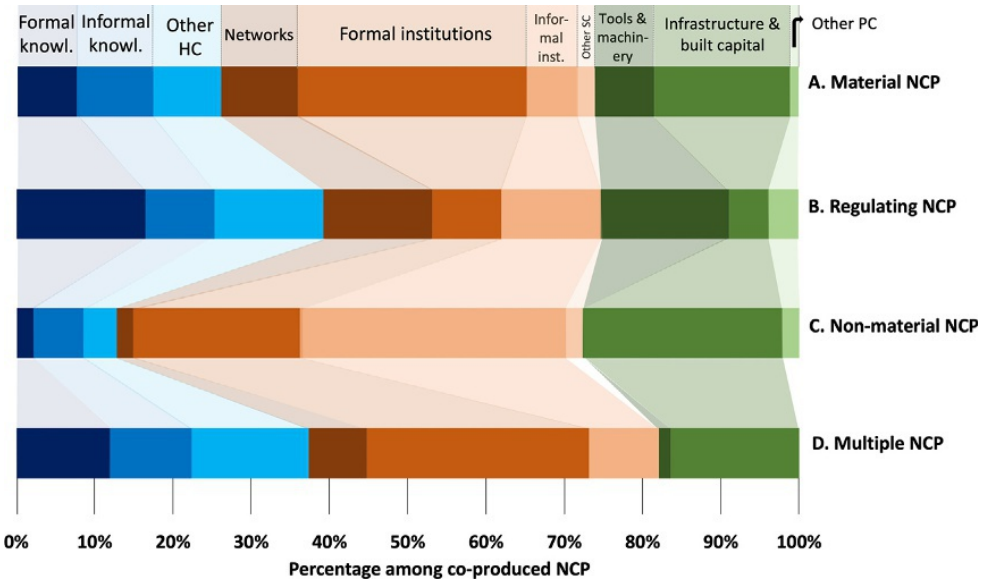


Fig. 5 Percentage of references in the reviewed literature made to anthropogenic capitals involved in nature's contributions to people (NCP) co-production (Abbreviations: knowl. = knowledge, HC = human capital, inst. = institutions, SC = social capital, PC = physical capital). Each anthropogenic capital in the top row is highlighted in a specific colour. Follow the transparent colourway to see how capitals contribute to each NCP group. When a capital does not contribute to a NCP group, the transparent colourway is minimised.

4.3 Governing anthropogenic capitals in the co-production of nature's contributions to people

The literature studies the governance of NCP co-production in multiple ways. However, of the 36 publications we reviewed that included governance of co-produced NCP, only seven publications referred to co-production explicitly (Auer et al., 2017; Felipe-Lucia et al., 2015; Garcia-Llorente et al., 2015; Lavorel et al., 2020; Malinga et al., 2018; Torralba et al., 2018; Vialatte et al., 2019). Despite having in common that they all explicitly refer to co-production, Auer et al. (2017) and Garcia-Llorente et al. (2015) only refer to it on a side-note while the other authors have integrated the concept throughout their publications (Felipe-Lucia et al., 2015; Lavorel et al., 2020; Malinga et al., 2018; Torralba et al., 2018; Vialatte et al., 2019).

The Multiple Correspondence Analysis (MCA) represents the connections between NCP, anthropogenic capitals, and governance modes, as researched in the scientific literature (Fig. 6). The first two factorial axes of the MCA accumulated 66% of the total inertia (Fig. 6A). The first axis (48%) revealed that the governance modes behind the management of the anthropogenic capitals underpinning the provision of NCP varied

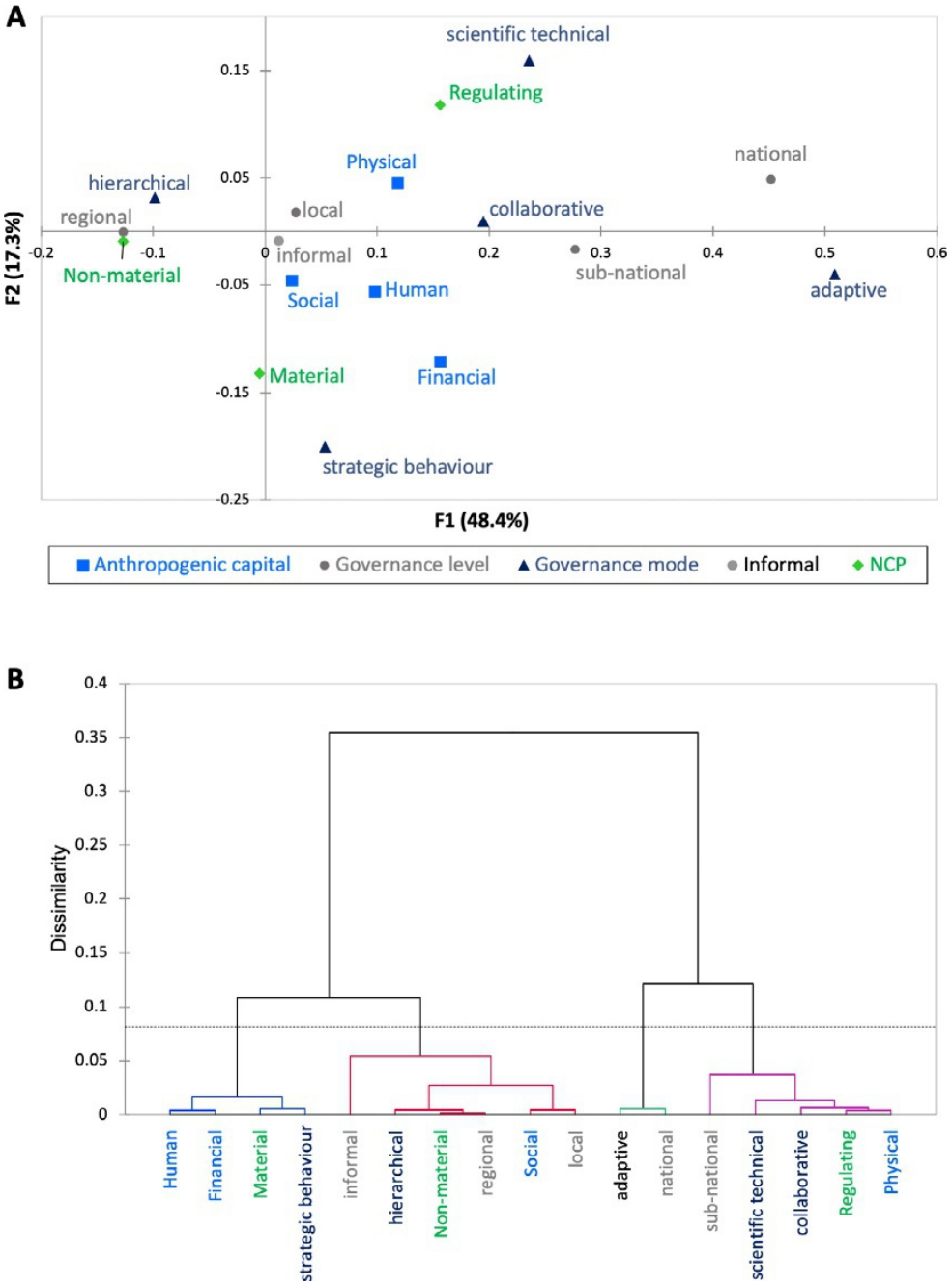


Fig. 6 Multiple correspondence analysis (MCA) and hierarchical cluster analysis (HCA) represent the connections between nature's contributions to people (NCP), anthropogenic capitals and governance modes. (A) MCA biplot, which factors 1 and 2 account for 48.4% and 17.3% of the inertia, respectively. The relative closeness of the variable positions along the axes reflects their tendency to be associated in the scientific literature. (B) Dendrogram of the hierarchical cluster analysis (HCA) performed with the MCA factors. The Bray and Curtis distance and Ward's Method were used as agglomerative techniques.

between non-material (in negative scores) and regulating NCP (in positive scores). Axis 2 (17%) distinguished the scientific literature that studied the governance of NCP co-production of regulating (in positive scores) and material NCP (in negative scores).

The Hierarchical Cluster Analysis (HCA) revealed three clusters representing different ways of researching governance of anthropogenic capitals that underpin NCP provision (Fig. 6B). The first cluster represents a group of literature that researched material NCP as mainly co-produced through an interplay of natural capital with human and financial capital. The governance mode related to this cluster is the governing of strategic behaviour (Fig. 6B). The second cluster represents the co-production of non-material NCP, which mostly involved social capital and hierarchical governance operating at regional and local scales and through informal institutions (Fig. 6B). The third cluster represents the scientific literature that researched regulating NCP. This cluster shows that regulating NCP are mainly co-produced by natural and physical capital and subject to scientific-technical and collaborative governance, operating at the sub-national level (Fig. 6B).

5. Discussion

5.1 Research trends on the governance of NCP co-production

Research on ecosystem services has increased exponentially over the last two decades (Droste et al., 2018; Luederitz et al., 2015). Although not rising exponentially and still underrepresented in ecosystem services literature compared to other research topics (Droste et al., 2018), the governance of ecosystem services has gained growing attention in recent years (Winkler et al., 2021). Similarly, the co-production concept is slowly permeating the literature on ecosystem services and NCP, but has been recently applied in various contexts (see e.g., Bruley et al., 2021; Fischer and Eastwood, 2016; Grosinger et al., 2021; Lavorel et al., 2020). Considering these developments and the results of this review, we can conclude that governance of NCP co-production is currently under-researched and yet to be explored in detail.

The fact that the governance of NCP co-production is a topic that has been traditionally overlooked entails a limitation for this review. Namely, the data availability for our review was relatively small when compared to much larger and more broadly focussed reviews on ecosystem services

(see e.g. Chaudhary et al., 2015; Droste et al., 2018) and the governance of ecosystem services (see e.g. Winkler et al., 2021).

5.2 Methods in research on the governance of NCP co-production

Our review's results revealed that research on the governance of NCP co-production is predominantly based on social science methods that gather mainly qualitative data (Fig. 1). For example, Vialatte et al. (2019) used in-depth interviews and focus groups for a socio-cultural valuation among farmers in France. Malinga et al. (2018) used a mixed methods approach including in-depth interviews, expert assessments and participatory mapping paired with biophysical data to quantify NCP in agricultural contexts in South Africa. Similarly, Winkler et al. (2021) highlight that more than half of ecosystem services governance literature uses qualitative data. By contrast, the ecosystem service literature is dominated by ecological and economic methods and quantitative data (see e.g. Fagerholm et al., 2016; Liquete et al., 2013; Martín-López et al., 2019; Nieto-Romero et al., 2014). Liquete et al. (2013), for example, found that marine and coastal ecosystem services are mainly studied using environmental science methods and quantitative data. Similarly, Nieto-Romero et al. (2014) found that most literature on ecosystem services in Mediterranean agroecosystems used economic, environmental or forestry science methods, while Martín-López et al. (2019) point out that biophysical methods dominate research on NCP in mountains.

In line with the findings by Winkler et al. (2021), our review showed that research on the governance of NCP co-production is mostly focused at regional and local scales, which might be due to the availability of data in regionally administered statistical databases. Another potential explanation is that most studies were conducted using social science methods involving local stakeholders (e.g. interviews), which aligns with the fact that more than half of the research on the governance of NCP co-production uses primary data.

5.3 Geographic distribution

Similar to several other reviews on ecosystem services and NCP (Haase et al., 2014; Liquete et al., 2013; Martín-López et al., 2019), our results showed that most case studies are located in Europe, Spain being a hotspot of research on the governance of NCP co-production. In contrast to the

reviews by Chaudhary et al. (2015) and Luederitz et al. (2015), who investigated ecosystem services in general and found most case studies were being conducted in the United States, our findings only show six case studies of co-produced NCP in the United States. Similar to Winkler et al. (2021), we found few case studies on the African continent outside of South Africa. While we found some case studies in Colombia, Brazil, China, India and South-East Asia, for example, a research gap exists regarding the governance of NCP co-production in most other countries across Asia and Latin America. Similar to Liquete et al. (2013), Luederitz et al. (2015), and Martín-López et al. (2019), we found no research conducted in Russia. Thus, future studies should aim to close these gaps by conducting further research in smaller countries of the African and Asian continent, across America, particularly in Russia, which appears to be under-researched.

5.4 Governing anthropogenic capitals in NCP co-production

Our results showed that material and regulating NCP are most studied in the NCP co-production governance literature. By contrast, Martín-López et al. (2019) found that most studies on NCP in mountains studied multiple NCP. When looking at multiple NCP, our review showed that food and feed appear in the three most common combinations of NCP (Fig. 4).

Our results also revealed that most research looked at the interplay of natural capital with multiple anthropogenic capitals. This result contrasts with the review by Kachler et al. (under review), which found that literature on ecosystem services co-production mainly focused on material and non-material NCP and human and physical capitals. Besides, our results showed that anthropogenic capitals in NCP co-production are predominantly governed on the local and regional levels. This is comparable to the results obtained by Winkler et al. (2021), who found most NCP governed on the regional and then on the local level. Regarding the modes of governance, our results paint an ambivalent picture compared to the findings by Winkler et al. (2021). In contrast to Winkler et al. (2021), we could not single out one mode of governance as predominant since our findings show that most anthropogenic capitals in NCP co-production are subject to multiple modes of governance. However, in line with Winkler et al. (2021), we found that hierarchical governance is the single most studied governance mode, while collaborative and scientific-technical governance are studied the least. Besides, Winkler et al. (2021) found governing of strategic

behaviour to be studied second most often while we found that it is only studied in combination with other forms of governance and thus appears as multiple modes of governance in our findings. Thus, our finding that anthropogenic capitals are predominantly governed by multiple modes of governance suggests that governance pluralism supports the co-production of NCP.

While Droste et al. (2018) found that agriculture is only the sixth most referred topic in ecosystem services research between 2001 and 2016, our analysis showed that most material NCP found in the literature on the governance of NCP co-production are defined as food and feed and thus related to agriculture. This also explains the strong link between material NCP and the capitals involved in their co-production. Human capital in the form of skills, local ecological knowledge and farming specific knowledge, and financial capital in the form of subsidies, direct payments and investments are necessary for viable agricultural production (see e.g. Garrido et al., 2017; Lavorel et al., 2020). As the agricultural sector, particularly within the European Union (EU), is heavily impacted by subsidies and direct payments (Simoncini et al., 2019), it thus comes as no surprise that these capitals behind the co-production of material NCP are influenced by the governing of strategic behaviour at the supra-national level (Fig. 6), which in this case refers to the EU's Common Agricultural Policy.

Similar to other reviews (see e.g. Fagerholm et al., 2016; Haase et al., 2014; Martín-López et al., 2019), we found regulating NCP to be the second most studied group of NCP (Fig. 4). In contrast to Haase et al. (2014) and Fagerholm et al. (2016) but comparable to Martín-López et al. (2019), we identified regulation of freshwater quality as well as regulation of soils and sediments as the most studied regulating NCP. These were predominantly co-produced by physical capital (Fig. 6), for example, in the form of irrigation canals for the regulation of freshwater quantity and quality (Garcia-Llorente et al., 2015) or tillage machinery in the management of soils (Dietze et al., 2019). Anthropogenic capitals underpinning regulating NCP co-production were found to be impacted by scientific-technical and collaborative governance modes (Fig. 6). For example, Garcia-Llorente et al. (2015) highlight that the involvement of local stakeholders predominantly drives collaborative governance on Spanish irrigation systems. Likewise, Hill et al. (2019) stress the importance of local Indigenous knowledge and its transmission through collaborative governance in the management of pollination NCP. Similarly, Hickey and Badry (in this special issue) explore ways of advancing collaborative governance to integrate Indigenous knowledge into

decision making better. Besides, Hill et al. (2019) also refer to several national and international policies securing traditional customary laws that support pollination. The integration in legal documents implies a recognition of local Indigenous knowledge in decision-making processes and thus serves as an example on how scientific-technical governance is behind the management of regulating NCP.

Similar to Fagerholm et al. (2016), our results revealed that psychological and physical experiences are the most studied non-material NCP (Fig. 4). Besides, we found that social capital contributes most to non-material NCP and is governed hierarchically on the regional and local level. This finding can be ascribed to promoting tourism and local recreation in protected areas such as national parks (Mannetti et al., 2017) or urban green spaces and infrastructure (Brown et al., 2020).

5.5 Research outlook

The clusters of governance modes affecting anthropogenic capitals in NCP co-production discussed above reveal several knowledge gaps within the literature. First and in line with Fagerholm et al. (2016)[a], we found that the most studied NCP within the literature were material and regulating. However, the anthropogenic capitals contributing to their co-production, namely human, physical, and financial capital, are the least-studied. Second, like Winkler et al. (2021), we found that collaborative and scientific-technical governance are the least-studied modes of governance overall. Nevertheless, these governance modes are most strongly related to the regulating NCP. This is crucial for further research on pluralism in NCP governance as collaborative and scientific-technical governance involve a variety of state and non-state actors, but since regulating NCP affect all parts of society. Hence, future research should focus on better understanding the role of collaborative and scientific-technical governance modes in the management of human, physical and financial capitals behind the co-production of material and regulating NCP. In the light of ever-increasing challenges due to climate change and biodiversity loss, these insights may be crucial to improve adaptive decision making for the management of NCP based on scientific data and inclusive stakeholder engagement.

[a] In contrast to Fagerholm et al. (2016) we did not refer to supporting ecosystem services in our review explicitly as they are already incorporated within the eighteen generalised NCP (Martín-López et al. 2018).

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Disclosure statement

The authors reported no potential conflict of interest.

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Chapter III

Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis

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Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis

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ABSTRACT

Forests support human wellbeing by providing multiple nature's contributions to people (NCP). These are derived from an interplay of both natural and anthropogenic assets, which is a process known as NCP co-production. Like forests and NCP, anthropogenic assets are subject to modes of governance operating across multiple levels, in which policies are a central tool for executing formal governance. Here, we conduct a policy document analysis to investigate how policies refer to both the anthropogenic assets involved in NCP co-production and the modes of governance affecting these, i.e., hierarchical, scientific-technical, (adaptive)-collaborative governance, and the governing of strategic behaviour. The policy document analysis focuses on forestry and biodiversity conservation policies spanning across multiple governance levels, from the local level – two Biosphere Reserves and one National Park in Germany – to the supra-national level of the European Union. We find that policies predominantly address material and regulating NCP and refer to hierarchical and scientific-technical governance. Based on a redundancy analysis, we identify six archetypes of governance of NCP and the anthropogenic assets underpinning their co-production: (1) *the governing of strategic behaviour for regulating NCP*, (2) *governing habitat management for experiences in nature*, (3) *governing habitat management for pest control*, (4) *collaborative governance for timber*, (5) *local governance for experiences in nature*, and (6) *promoting knowledge for habitat protection*. Our analysis thereby unveils how policies intend to govern anthropogenic capitals related to the co-production of specific forest NCP. The findings, including the six archetypes, can support policymakers in designing policies across governance levels.

1. Introduction

Forests are multifunctional and support human wellbeing by providing multiple material, non-material, and regulating nature's contributions to people (NCP) (Díaz et al., 2018; Felipe-Lucia et al., 2018; Plas et al., 2018; Teben'kova et al., 2020). Forest NCP are either wood based, i.e., timber production or biomass energy, or non-wood based, i.e., foraging of wild edible plants, microclimate regulation, carbon sequestration, and recreational activities. Similarly to other ecosystems, forest NCP are no mere 'free gift' provided by nature (Spangenberg et al., 2014), but co-produced by humans in an interplay between nature and anthropogenic assets, such as forestry machinery or forest management practices (Palomo et al., 2016). This process is known as NCP co-production and recognised by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES) in its framework (Díaz et al., 2018; Kadykalo et al., 2019; Peterson et al., 2018). Recently, the co-production concept has been applied across ecosystems, including forests, to better understand the role humans play in the provision of ecosystem services and NCP (e.g., Bruley et al., 2021; Grosinger et al., 2021; Jericó-Daminello et al., 2021; Palliwoda et al., 2021; Torralba et al., 2018). Fischer and Eastwood (2016) refer to various co-produced forest NCP, for example based on suitable machinery to access timber from a local estate for producing arts and crafts. Similarly, regulating NCP in forests can be supported by the input of anthropogenic assets. Lavorel et al. (2020), for example, stress the importance of agroforestry practices in minimising heat stress and regulating the local microclimate by creating shade through increased tree cover. Likewise, Bruley et al. (2021) showcase the need for manual labour when planting trees on slopes in alpine settings, which contributes to mitigating the risk of avalanches.

In this paper we employ the NCP co-production concept on forests by applying the framework developed by Palomo et al. (2016) who identify

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four sources of anthropogenic assets, also known as capitals: human, social, physical, and financial capital. Human capital includes people's knowledge, skills, health, and manual labour. It is embodied in many forest management practices, such as operating machinery, planting or felling trees, and managing habitat. Social capital refers to all human-to-human relationships operating in networks as well as formal and informal institutions. In the forest context, this entails forestry associations, or legal requirements, such as laws, regulations, or certifications regarding forest management and timber harvest. Physical capital encompasses all tools and machinery. In the context of forest management, for example, this applies to chainsaws, harvesters, forwarders, or trucks, as well as infrastructure, such as skid trails or logging roads. Financial capital concerns all monetary assets in the form of savings, credit payments, or direct governmental payments used to support the provision of forest NCP. More detailed definitions of anthropogenic capitals and forest-specific examples can be found in Appendix A.

Both, the NCP provided by forests and the anthropogenic capitals co-producing these, are subject to various forms of governance in both formal and informal settings spanning across multiple levels (Aggestam and Pülzl, 2018; Arts, 2014; Juerges et al., 2020; Mann et al., 2022; Primmer et al., 2021). Governance in the European context, for example, includes state and non-state actors and spans across levels ranging from the local, to the subnational, to the national state level, and finally to the supra-national level of the European Union (EU) level (Arts, 2014; Hooghe et al., 2001). This sharing of power in decision-making processes has been described as multi-level governance (Arts, 2014; Arts and Visseren-Hamakers, 2012; Hooghe and Marks, 2010). The competence to govern forests and their contributions to people through policy, however, lies with the national member states and their respective sub-ordinate levels rather than with the EU (Primmer et al., 2021; Winkel et al., 2022; Wolfslehner et al., 2020). This contrasts the governance of other ecosystems and NCP they provide, for example in agricultural settings (Plieninger et al., 2012; van Zanten et al., 2014). These are strongly influenced by policies at the EU level, for example via the Common Agricultural Policy (CAP) (Bouwma et al., 2018). Nonetheless, EU policy can have indirect effects on the provision of forest NCP, for example through energy policy or trade regulations (Rivera León et al., 2016). In this article we follow the policy definition by Bouwma et al. (2018) who included both "1) binding legislative instruments, such as directives, regulations, and decisions, and 2) non-binding programme instruments, such as strategies, recommendations, and communications" (p.2) in their document analysis of EU policies.

In line with the general trend of power dispersion across governance levels in many policy fields (Wolfslehner et al., 2020), forest governance within the EU is often described to be fragmented since decision-making competences remain with approximately 90 governance units across the member states and their subsidiary levels (Edwards and Kleinschmit, 2013; Elomina and Pülzl, 2021; Lazdinis et al., 2019). Thus, power asymmetries between the EU and its member states in favour of the latter exist and an ongoing dispute about competencies has been observed (Edwards and Kleinschmit, 2013; Lazdinis et al., 2019; Winkel et al., 2022). Due to the lack of competence in governing forest, decision-makers at the EU level encounter difficulties to design forest policies (Lazdinis et al., 2019). For one, an "ideological polarisation between environmental/conservation and forest use interests" has been observed in EU forest policy (Winkel et al., 2022, p. 4). Second, coordination of forest policy across the EU has been challenging due to its "soft" nature (Lazdinis et al., 2019, p. 1739).

Despite a lack of competence, policies at the EU level acknowledge forests as providers of wood and non-wood products (material NCP), as essential ecosystems to mitigate climate change, regulate soils, water, and natural hazards (regulating NCP), and as relevant for fostering people's physical and psychological wellbeing (non-material NCP) (Elomina and Pülzl, 2021). The multifunctionality of forests is also recognised by the EU's Forest Strategy since it highlights the importance of sustainable forest management in the provision of multiple forest NCP and for tackling biodiversity loss and climate change (Hernández-Morcillo et al., 2022). Whilst the provision of multiple NCP by forests is recognised by policy documents at the EU level, Primmer et al. (2021) show that forest-related documents on the EU and member state levels nonetheless predominantly focus on wood (material NCP) and maintenance of habitats and biodiversity (regulating NCP). Forest policy in Germany, for example, has long been focusing on timber production (Sotirov and Storch, 2018) but described to fulfil other societal demands through forest use (Borrass et al., 2017). Recently, specific policy documents have accounted for different forest NCP more specifically. The German Forest Strategy 2020, for example, recognises a range of non-material NCP, such as recreation and hunting (Hochmalová et al., 2021).

Policies intend to govern forests and their contributions to humans in various ways depending on the institutional setting and administrative system in which decision-making takes place (Pülzl et al., 2013). Forest governance has marked a shift in moving beyond strict top-down regulation to more inclusive modes of governing (Arts, 2014). These encompass approaches such as nature focussed forest management, local implementations of certification schemes for sustainable forest management, or payments of ecosystem services (Loft et al., 2022). Recent studies have proposed a range of improvements for forest governance modes, including, amongst others, the broadening of monitoring approaches to account for changes in societal demands towards forests, especially regarding non-material NCP (Weiss et al., 2022; Winkel et al., 2022), the integration of forest related policies from different policy fields to create coherence (e.g., Beland Lindahl et al., 2023; Edwards and Kleinschmit, 2013; Winkel et al., 2022); increasing stakeholder participation on local and regional levels to facilitate the incorporation of societal value changes into forest policy (Hernández-Morcillo et al., 2022; Weiss et al., 2022; Winkel et al., 2022). The existing and proposed governance modes outlined above resonate with the framework defined by Primmer et al. (2015), who differentiate between four broad, yet interacting, modes of governance: hierarchical, scientific-technical, and (adaptive-) collaborative governance, as well as the governing of strategic behaviour. While hierarchical governance is based on top-down policy implementation, (adaptive-) collaborative governance seeks to involve multiple stakeholders, for example, in bottom-up processes. To gain a more nuanced understanding of the governance of NCP co-production, Isaac et al. (2022b) further differentiate between adaptive and collaborative governance. Adaptive governance describes the responses to changes in the social or ecological system, which are often organised polycentrically and involve various decision-making centres (Folke et al., 2005). Whilst collaborative governance is not necessarily adaptive, adaptive governance relies on the collaboration between stakeholders and decision-makers at different governance levels (ibid.). Scientific-technical governance is based on technical specifications and scientific arguments, whereas the governing of strategic behaviour refers to lobbying efforts and incentivising stakeholders through monetary payments (Primmer et al., 2015). Appendix B provides an in-depth overview of all modes of governance with examples from forest policies.

The governance of forests and their contributions to human wellbeing is covered by an extensive body of literature (e.g., Aggestam and Pülzl, 2018; Hernández-Morcillo et al., 2022; Hochmalová et al., 2021; Juerges et al., 2020; Primmer et al., 2021; Winkel et al., 2022). The challenges in governing forests through policy as outlined above resonate with the NCP co-production concept as various governance modes target specific anthropogenic capitals. Generating new knowledge in the monitoring of NCP and accounting for changes in people's values towards forests, for example, align with the human capital category. Similarly, improving stakeholder participation is a way of promoting social capital. Besides, the IPBES conceptual framework recognises governance as a main driver in the use of anthropogenic capitals in the co-production of NCP. Nonetheless, little research on the formal

governance of anthropogenic capitals in this interplay exists (Isaac et al., 2022b). We address this research gap by asking: How are anthropogenic capitals in the co-production of forest NCP formally governed across governance levels? We seek to answer this research question by conducting a policy document analysis to (i) explore how policies from the local to the supra-national EU governance level address the co-production of NCP in forests, (ii) analyse if and how policies acknowledge the different anthropogenic capitals involved in the co-production of NCP, and (iii) identify archetypes of governance of NCP and the anthropogenic assets underpinning their co-production. We focus on three case study sites across Germany that have been part of the long-term biodiversity research project *Biodiversity Exploratories* and are governed across multiple levels. By exploring the influence of governance across these levels on the co-production of forest NCP this research can thus not only contribute to the scientific debate but be beneficial to decision-makers when designing forest policy and regulating the use of specific capital types.

2. Governance levels, policies, and data analysis

2.1. Case study sites

The Biodiversity Exploratories are a large-scale and long-term biodiversity research project investigating the impacts of land-use on biodiversity and ecosystem functioning in grasslands and forests. The project has recently broadened its focus to the effects of social systems on the provision of NCP (Fischer et al., 2010; Le Provost et al., 2022; Peter et al., 2022). The Biodiversity Exploratories include three rural case study sites across three federal states in Germany: Schorfheide-Chorin in Brandenburg in the North East, Hainich-Dün in Thuringia in the country's centre, and Schwäbische Alb in Baden--Württemberg in the South West (Fischer et al., 2010) (Fig. 1). Whilst varying in location, physical, and social parameters (Table 1), forests cover large parts of all three case study sites. According to Fischer et al. (2010), 13% of forests within the Biodiversity Exploratories' 500 forest grid plots were unmanaged, 83% managed age-class forests, and 4% selection forests. Most unmanaged forests (28%) were found in Hainich-Dün.

The case study sites are embedded in a multi-level formal governance system spanning from the local, across the federal-state (*Bundesland*), and the federal level of Germany (*Bundesrepublik*) to the European Union (Fischer et al., 2010; Grotz, 2012). Besides, all three Biodiversity Exploratories include formally protected areas. The Schorfheide-Chorin and Schwäbische Alb case study sites encompass a UNESCO[1] Biosphere Reserve each, while the Hainich-Dün case study site contains the Hainich National Park (Biodiversity Exploratories, 2022) (Table 1).

2.2. Policy document analysis

2.2.1. Selection of policies

We conducted a policy document analysis to identify archetypes of governing anthropogenic capitals in the co-production of forest NCP by considering multiple governance levels ranging from the local to the European Union. Policy document analysis helps to investigate the "nature of a policy document in order to look at both what lies behind it and within it" as Cardno (2018), p. 625 points out. Since up to 570 forest policy documents on the EU level alone address forest governance, we selected forest-related policy documents across in an iterative four-step approach (Rivera León et al., 2016). First, we checked policy documents referred to by relevant scientific literature (e.g., Bouwma et al., 2018; Hochmalová et al., 2021; Schleyer et al., 2015; Winkel et al., 2013; Wolfslehner et al., 2020). Second, we conducted an online search for forest and biodiversity conservation-related policy documents in online databases of the European Union, German national and federal-state ministries, state forest agencies, the Biosphere Reserves of Schorfheide-Chorin and Schwäbische Alb, and the Hainich National Park. Appendix C lists these databases and websites. Third, we used *QGIS* Version 3.28.1 Firenze to assess which Natura 2000[2] Management Plans affected protected forests in the three case study sites by overlaying the borders of Natura 2000 areas with the geospatial data of the Biodiversity Exploratories' plots. Finally, we interviewed 37 forest managers and 13 conservationists in the three study sites about the policy documents relevant for their work. For further information on the interview guide, see the fieldwork protocol (Isaac et al., 2022a). Based on our search, we found 96 policy documents that mostly focussed on biodiversity conservation (n = 55) and forestry (n = 27) as well as other themes such as rural development (n = 6), agriculture (n = 3), sustainable development (n = 3), land-use (n = 1), and energy (n = 1) (Fig. 2). Of these 96 policy documents, 76 met our selection criteria by referring to the governance of anthropogenic capitals in NCP co-production in forests. For a comprehensive overview of selected policy documents see Appendix D.

2.2.2. Content analysis

We conducted a content analysis of the 76 policy documents. "Content analysis is the process of organising information into categories related to the central questions of the research" as Bowen (2009), p. 32 stresses. This process is either organised inductively by deriving categories from the text or deductively by applying predefined categories to find emerging themes (Cardno, 2018). A deductive approach to content analysis, as employed here, is thus based on the interpretation of text according to predefined categories or codes rather than applying rigid indicators (Bowen, 2009; Cardno, 2018). We applied a deductive coding set based on the capitals definition by Palomo et al. (2016) and the governance modes proposed by Primmer et al. (2015), which had already been proven to be beneficial in analysing the governance of NCP co-production (Isaac et al., 2022b). The coding set, including definitions of the predefined categories extracted from the established literature on NCP co-production and governance, can be found in Appendix E.

In addition to anthropogenic capitals and governance modes, we also coded the governance level (from local to EU, Fig. 2), and focussed on ten co-produced NCP that the policy documents intended to govern. These NCP represent the multifunctionality of forests, spanning from material (i.e., timber production, food), to regulating (i.e., habitat creation and maintenance, regulation of climate, regulation of detrimental organisms, regulation of hazards and extreme events, and soil formation and protection), to non-material NCP (i.e., bird watching, cultural experiences through plants, other physical or psychological experiences) (Felipe-Lucia et al., 2018). In line with the generalising perspective on NCP by the IPBES, regulation of climate addresses both carbon sequestration and micro-climate regulation (Díaz et al., 2018; Martín-López et al., 2018). Whilst the policy documents refer to a variety of forest NCP and anthropogenic capitals, we want to highlight that only statements were coded for this content analysis in which anthropogenic capitals were described to co-produce a specific forest NCP. Hence, references made to NCP provided by forests without the contribution of anthropogenic capitals were not included in the analysis. Verbatims from the policy documents describing specific forest NCP can be found in Table 2 and Appendix F, while verbatims describing the anthropogenic capitals can be found in Table 3 and Appendix G. Finally, we gathered data on general information, such as the year of publication, policy type, the

[1] United Nations Educational, Scientific and Cultural Organization (UNESCO).

[2] Natura 2000 is an EU wide network of areas protected under the EU's Habitats Directive (92/42/EEC) and the Birds Directive (2009/147/EC) that includes a variety of habitats, for example, beech forests, semi-natural dry grasslands, and fixed coastal dunes (European Commission, 2022; Wolfslehner et al., 2020).

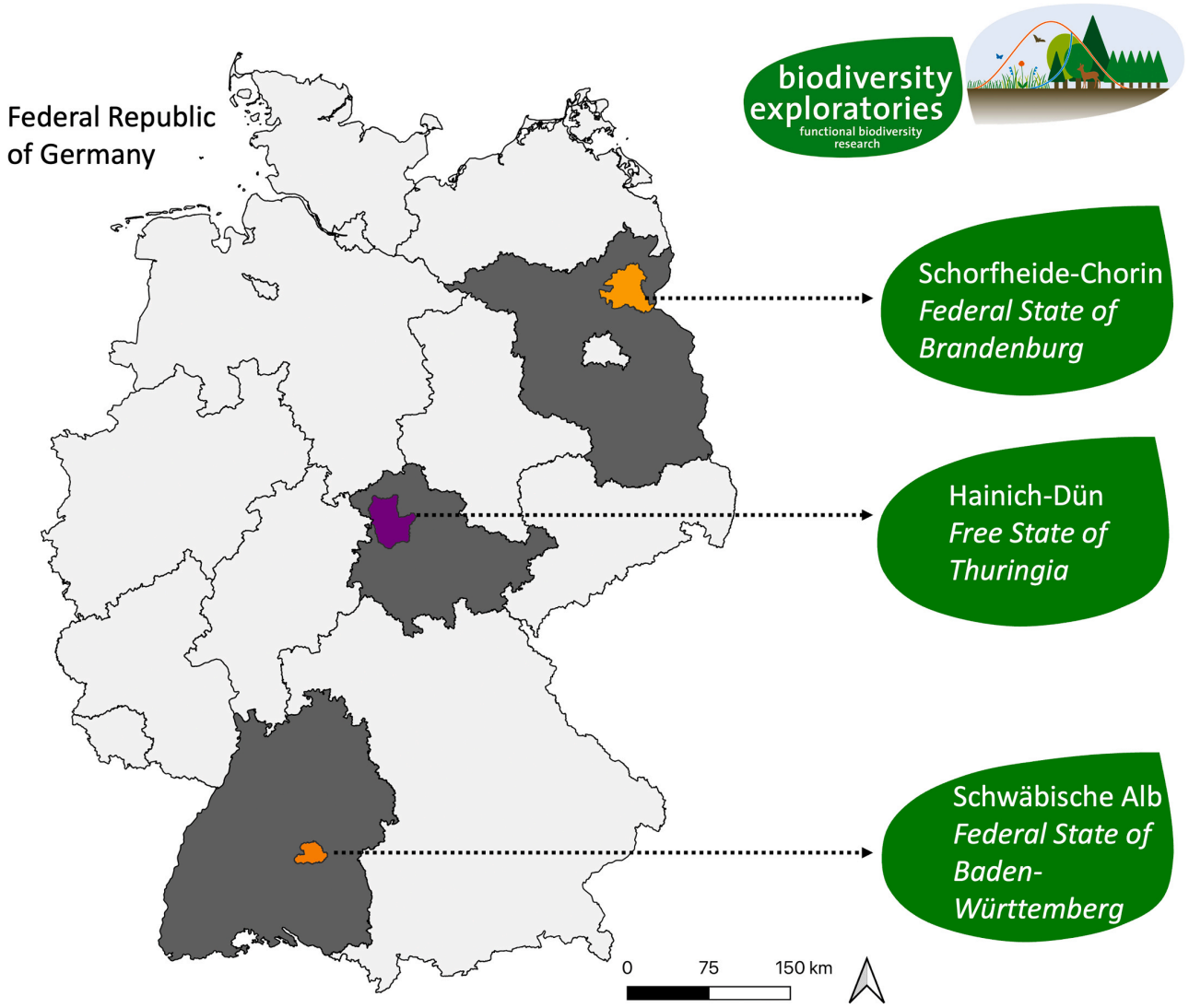

Fig. 1. Biodiversity Exploratories' case study sites within Germany. Coloured areas show the three case study sites while outlines show the federal states of Germany. The orange case study sites include UNESCO Biosphere Reserves, while the purple case study site includes a national park.
This figure is based on data by the Biodiversity Exploratories Information System (BExIS) (2022) and Esri Deutschland GmbH (2018).

Table 1
The Biodiversity Exploratories' main characteristics. Adapted table from Fischer et al. (2010, p. 276).

	Schorfheide-Chorin	Hainich-Dün	Schwäbische Alb
Location	NE Germany	Central Germany	SW Germany
Federal-state	Brandenburg	Thuringia	Baden-Württemberg
Size	~1300 km^2	~1300 km^2	~422 km^2
Altitude a.s.l.	3–140 m	285–550 m	460–860 m
Annual mean temperature	8–8.5 ∘ C	6.5–8 ∘ C	6–7 ∘C
Annual mean precipitation	500–600 mm	500–800 mm	700–1000 mm
Human population density	23 km− 1	116 km− 1	258 km− 1
Main protection status	Biosphere Reserve	National Park	Biosphere Reserve

level at which the policy was published, and the administrative level that the policy document addresses.

2.2.3. *Statistical analysis*

We used descriptive statistics to detect how policy documents relate anthropogenic capitals to NCP co-production and connected these to the modes of governance. To determine which combinations of anthropogenic capitals and NCP are governed most commonly by the policy documents, we generated a heatmap by using *R Studio* 2022.07.0 Build 548. For the statistical analysis, we excluded those NCP mentioned in less than 5% of cases in the policy documents. In addition, we conducted Chi-square tests to identify associations between each governance level and NCP categories, anthropogenic capitals, and governance modes.

In order to identify the archetypes of governance of NCP and the anthropogenic assets, we conducted a Redundancy Analysis (RDA). Redundancy Analysis (Rao, 1973) is a multivariate approach of linear models, where the linear model is generated with a matrix of dependent variables (Y matrix). RDA builds a Principal Component Analysis with the dependent variables (Y matrix) under the premise that the resulted

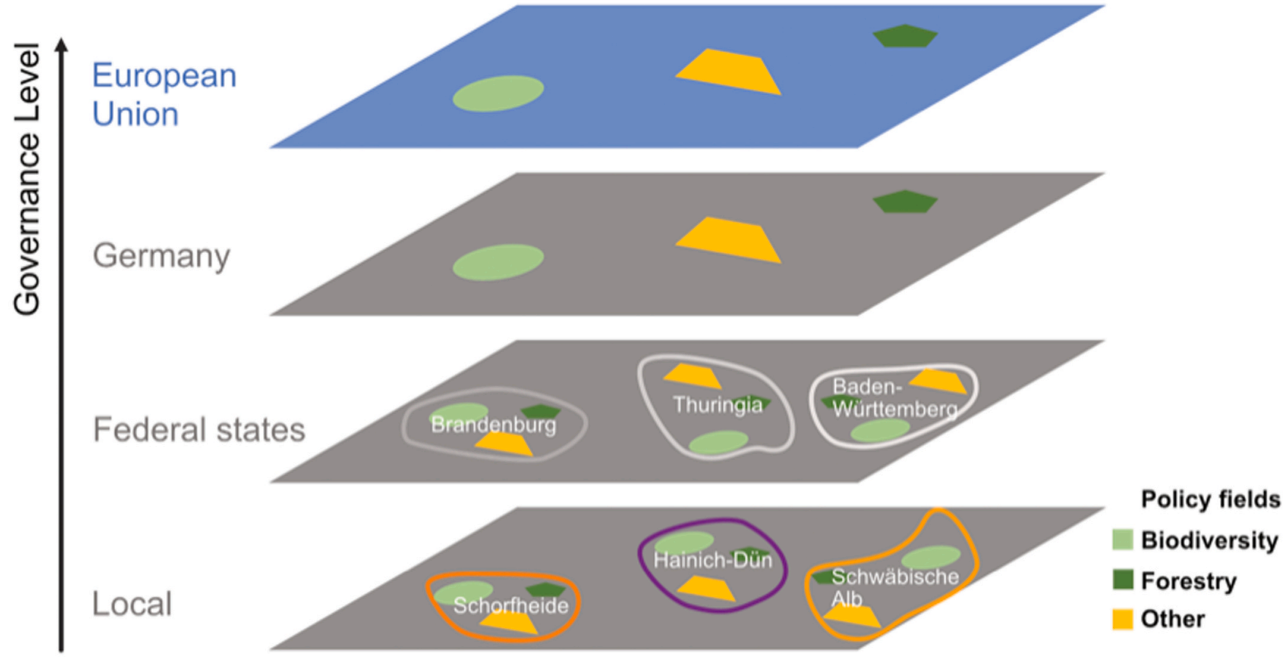

Fig. 2. Embeddedness of the Biodiversity Exploratories case study sites (Schorfheide, Hainich-Dün, and Schwäbische Alb) in the European Union's multi-level governance system.

axes are also linearly explained by the explanatory variables (X matrix). Therefore, RDA is generally used to determine patterns of interactions between dependent variables (here, NCP and anthropogenic capitals) and between these and independent variables (here, governance modes and governance levels). RDA has been suggested as a suitable quantitative method to examine whether associations of NCP can be explained by a set of environmental and socio-cultural factors (Mouchet et al., 2014). In fact, RDA has been broadly used in ecosystem services and NCP research to determine patterns of interactions between landscape features and NCP supply (e.g., Schmidt et al., 2019; Zoderer et al., 2019), between socio-cultural variables and NCP preferences (e.g., Cebrián-Piqueras et al., 2020; Martín-López et al., 2012; Schmitt et al., 2021), or between drivers of change and NCP trends (e.g. Jaligot et al., 2019; Santos-Martín et al., 2019). In this paper, we used RDA to determine whether associations of NCP and anthropogenic capitals can be explained by modes of governance at different governance levels, resulting in different archetypes.

To evaluate whether the variation explained by the association between variables in the RDA axes is higher than would be explained by the same number of randomly generated variables, we performed a Monte Carlo permutation test (500 permutations). Therefore, the Monte Carlo permutation test provides evidence of the significance of the relationships between the governance variables and the NCP and anthropogenic capital variables. Moreover, the RDA provides a representation of the variables in two or three dimensions (Legendre et al., 2011), which is optimal for a covariance criterion (Ter Braak, 1992)and indicates the representativeness of each variable for each axis through their squared cosines.

Finally, we conducted ANOVA tests of the RDA axes to test whether the governance archetypes of NCP and anthropogenic capitals differ between the three BE sites. When the ANOVA tests achieved 95% significance, we used a post hoc Bonferroni pairwise comparison test.

2.2.4. *Methodological limitations*

This policy document analysis is based on a broad selection of documents from different policy fields. This holds several methodological limitations. First, and in contrast to other analyses (e.g., Bouwma et al., 2018; Elomina and Pülzl, 2021; Hochmalová et al., 2021; Primmer et al., 2021), we included policy documents from the federal-state and the local level. Thus, our analysis relied heavily on documents focussing on biodiversity conservation on the local level in the form of Natura 2000 management plans. Second, and despite broad selection of documents, a comprehensive analysis of forest-related policy documents remains challenging due to the sheer number of documents across governance levels. Thus, our analysis provides a snapshot on how anthropogenic capitals and the forest NCP they co-produce are governed policy documents. Third, in line with Bouwma et al. (2018) our analysis includes binding and non-binding agreements. Thus, our analysis does neither account for power asymmetries between different governance levels nor indicate whether the management of anthropogenic capitals and forest NCP on the ground is adjusted in line with the analysed policy documents. Hence, future research on governing anthropogenic capitals could address this gap (Isaac et al., 2023). Fourth, our analysis only provides a static view on this governance as it does not address dynamic changes in policymaking over time. Hence, further research could differentiate between specific periods when investigating the representation of anthropogenic capitals and the forest NCP they co-produce in policy documents.

3. Results

3.1. *Distribution of policy documents over time, across policy fields, policy types, and governance levels*

In total, we analysed 9399 pages across 76 policy documents related to the governance of anthropogenic capitals in the co-production of forest NCP. We did not find the term "co-production" or its synonyms, for example "coproduction" or "co-produce", related to NCP in any of the policy documents. Hence, NCP co-production was described implicitly throughout all policy documents analysed. Most policy documents assessed focussed on biodiversity conservation (58%, n = 44) and forestry (30%, n = 23). In comparison, only 7% of policy documents

Table 2
Portrayed nature's contributions to people (NCP) in policy documents that intend to manage forests. Verbatims represent examples on how material, non-material, and regulating NCP are referred to in the policy documents. Original verbatims in German can be found in Appendix F.

Nature's contributions to people		Exemplary verbatims (English translation)	Policy	Page (s)
Material	Timber production	*The goal of timber production, which occurs every 5 years, is ongoing forest management:* • *Harvest of valuable, harvestable trees according to quality and a defined diameter* • *Removal of damaged or dependent trees* • *Selection and raising* • *Mixed regulation to achieve shares in tree selection* • *Supporting tree offspring*	Directive on State-wide Forest Development Types Baden-Württemberg (2014)	4f.
	Food	*The restrictions in §44 paragraph 1 number 4 and paragraph 2 sentence 1no. 1 of the Federal Nature Conservation Law do not apply to the following mushroom species, if they are collected in small amounts in nature for personal use (…)*	Federal Species Protection Regulation (2005)	§2.1
Non-material	Birdwatching	*Conservation of existing spatial patterns and tree composition in stock, which are within the inner protection zone (100-m-radius and close to eyries of specially protected bird species, in particular in combination with measures to support rejuvenation, should only allow extraction of trees in single logs and outside the mating and breeding seasons of birds, as this is relevant for the following species* • *Red kite,* • *Black stork, and* • *Eagle owl (…).*	Technical Contribution Forests for the Natura 2000 Management Plan for Ibenkuppe - Thomasbrücke - Östlicher Westerwald and SPA Südliches Eichsfeld (2017)	21
	Cultural experiences through plants	*Nature conservation areas are legally binding areas, in which nature and landscape are especially protected in their entireness and in their singular parts, where it is needed for* *1. preserving, developing, or regenerating habitats, biotopes, communities of specific wild animal and plant species,* *2. scientific, natural history, or geographic reasons,* *3. or due to their rarity, specific characteristic, or outstanding beauty.*	Federal Nature Conservation and Maintenance Law (2009)	§23.1
	Other physical or psychological experiences	*Forests play an important role for physical and psychological regeneration of people and are intensively used for recreation, leisure activities, and sports, particularly in conurbation and outer conurbation areas.*	German Forest Strategy 2020 (2011)	29
Regulating	Habitat creation and maintenance	*(…) Protection of existing and formally protected forest biotopes in their current spatial coverage, characteristic condition, and as habitat for the occurring biotope specific species in fauna and flora (is important), (…)*	Technical Contribution Forests for the Natura 2000 Management Plan for Muschelkalkhänge from Großbartloff to Faulungen and SPA Südliches Eichsfeld (2014)	16
	Regulation of climate	*Forests and the forestry sector are impacted by climate change but contribute to climate mitigation simultaneously. (…) Adapting forests to climate change can be done by selecting*	German Forest Strategy 2020 (2011)	22f.

(continued on next page)

Table 2 (*continued*)

Nature's contributions to people		Exemplary verbatims (English translation)	Policy	Page (s)
		suitable tree species and trees from origins that show respective climate variabilities.		
	Regulation of detrimental organisms	*Funding can be sought for (…) tackling detrimental organisms by finding and processing infested or potentially infested timber (e.g., by cleaning cuts, debarking, bark disposal, moving and transport of timber) or other measures that reduce the timber's suitability for breeding and thereby minimise or diminish potential further risks arising.*	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	110
	Regulation of hazards and extreme events	*Measures need to be in immediate relation to coping with damages due to extreme weather and the results of these (e.g., bark beetle) and the restoration of location specific and climate adaptive forests on the damaged areas.*	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	110
	Soil formation and protection	*The regeneration and protection of natural soil functions is essential to sustainable, careful, and proper forest management.*	Brandenburg Forest Law 2004	§4.3

(n = 5) were directed at rural development and 5% (n = 4) related to other sectors, such as bioeconomy, agriculture, or climate (Figs. 2, 3B).

The number of policy documents varied over time (Fig. 3A), with the first being implemented in 1969 (i.e., the German law on compensations for forest damages -*Forstschäden-Ausgleichgesetz*-). Most policy documents were published in 2015 (21%, n = 15), targeting the federal-state level. The policy documents also vary in legal status. Due to the large number of Natura 2000 sites in our case studies, Natura 2000 management plans made up 28% (n = 21) of the policy documents analysed. Laws and regulations both accounted for 17% (n = 13), while directives made up 13% (n = 10) and strategies 9% (n = 7). Other policy documents, for example, BR plans, amounted to 16% (n = 13). Most policy documents were written in German (83%, n = 63) and only 17% in English (n = 13). The latter were predominantly policy documents at

Table 3
Portrayed anthropogenic capitals involved in the co-production of forest NCP as stated by policy documents. Verbatims represent examples on how human, social, physical, and financial capital are referred to in the policy documents. Original verbatims in German can be found in Appendix G.

Anthropogenic capitals		Exemplary Verbatims (English translation)	Policy	Page (s)
Human capital	Labour	*Trees with the highest potential are to be specifically supported by targeted thinning and removal of oppressors.*	Silviculture Directive Brandenburg (2004)	8
	Knowledge	*To ensure the sustainable development of rural areas, it is necessary to focus on a limited number of core priorities relating to knowledge transfer and innovation in agriculture, forestry, and rural areas, (…) the sustainable management of forests, (…)*	EAFRD Funding Regulation (2013)	Article 1.4
	Skills	*By supplying silvicultural programmes, this directive provides the tools to enable forest owners to achieve their operational goals related to silviculture.*	Directive on State-wide Forest Development Types Baden-Württemberg (2014)	3
Social capital	Networks	*Forest management associations are associations of landowners under private law that aim to improve the management of the attached forest areas and those areas dedicated to afforestation, and overcome disadvantages related to small-sized forests, disadvantaged areas, fragmentation of ownership, general hotch-potch, insufficient forest openings, or other structural disadvantages.*	Federal Forest Law (1975)	§16
	Institutions	*Based on their competency, federal and state government agencies must support the implementation of nature conservation goals*	Federal Nature Conservation and Maintenance Law (2009)	§2.2

(*continued on next page*)

Table 3 (*continued*)

Anthropogenic capitals		Exemplary Verbatims (English translation)	Policy	Page (s)
		and landscape maintenance.		
Physical capital	Tools and machinery	*Use should be performed moderately for the soil and in deep frost. Timber should be moved by horse instead of establishing skid trails.*	Management Plan Poratzer Moränen-landschaft (2015)	217
	Infrastructure and built capital	*Forest roads serve forest development for the purposes of forest management and recreation of visitors.*	Baden-Württemberg State Forest Law (2019)	§19.1
Financial capital	Direct payments	*The payments cover 80% of proven spendings at max. according to number 3.2.1. Payments can cover up to 90% of proven spendings in case of small private landowners (under 20ha forest ownership).*	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	113
	Subsidies	*The forestry sector is to be financially supported by the state for the productive, protective, and social function of forests according to §1.*	Federal Forest Law (1975)	§41.1

the EU level. The policy documents covered various governance levels (Fig. 3C). Due to the large number of Natura 2000 management plans, most policy documents were implemented by authorities at the federal-state level (*Bundesländer*). Brandenburg accounted for 26% (n = 20) of all coded policy documents, Thuringia for 21% (n = 16), and Baden-Württemberg for 17% (n = 13). EU policy documents made up 18% (n = 14) whilst policy documents on the (German) national level accounted for 16% (n = 12). Only one policy document was authorised on the local level, namely by the Hainich National Park administration (1%). However, the policy documents often affected subsidiary levels and were intended to govern anthropogenic capitals on these. For example, the Maintenance and Development Plan for the Biosphere Reserve Schorfheide-Chorin is authorised by the Ministry of Agriculture, Environment and Climate Protection of the State of Brandenburg, but is applied to the Biosphere Reserve Schorfheide-Chorin. Thus, 18% of policy documents apply to the European Union, 16% to the territory of Germany, 25% across the federal states, and 41% across the three Biodiversity Exploratory case studies.

3.2. Governing anthropogenic capitals in the co-production of forest NCP

Across the 76 policy documents, we found 525 statements connecting our focal NCP with anthropogenic capitals and governance modes. The documents refer to forest NCP and anthropogenic capitals in multiple ways. Tables 2 and 3 provide exemplary verbatims representing each focal NCP and anthropogenic capital, respectively. Although they do not explicitly refer to co-production, some policy documents relate the use of anthropogenic capitals to the provision of NCP. The Directive on State-wide Forest Development Types Baden-Württemberg (2014), for example, stresses the importance of knowledge dispersion through management programmes to support timber production: "By including silvicultural programmes, this directive provides the tools to enable forest owners to achieve their operational goals related to silviculture" (p. 3). Other policy documents refer to them more subtly and implicitly, for example, when the Federal Nature Conservation and Maintenance Law (2009) refers to protecting wild plants for their "outstanding beauty" (§23.1). Tables, including the verbatims for NCP and anthropogenic capitals in German, can be found in Appendices E and F, respectively.

3.2.1. Focal NCP

Overall, we predominantly found references to anthropogenic capitals related to material (42%) and regulating NCP (34%). Non-material NCP only accounted for 24% of all co-produced NCP found in the policy documents (Fig. 4A). Timber production made up 91% of material NCP. In comparison, food was only mentioned in 9% of the statements. Despite this imbalance, some documents, such as the EU Forest Strategy for 2030 (2021), highlight the importance of both wood and non-wood material NCP. Regulating NCP were dominated by habitat creation and maintenance, appearing in 61% of the statements. The Silviculture Directive for the State of Brandenburg (2004, p.8) highlights the role of specific knowledge in the creation and maintenance of habitat when noting that "the planting of non-native plant species causes unpredictable harm to native flora and fauna and thus needs to be restricted". Other regulating NCP mentioned were the regulation of detrimental organisms (19%), the regulation of climate (10%), the regulation of hazards and extreme events (7%), as well as soil formation and protection (3%). Birdwatching was the most mentioned non-material NCP, found in 63% of the statements. The Biosphere Reserve Schwäbische Alb's Framework Concept Volume 3: Our Way (2012, p. 19), for example, aims at providing opportunities for birdwatching by designing and implementing "a forest bird monitoring (especially for woodpeckers and birds of prey) (…) in a way that it appeals to youth". Besides, the remaining non-material NCP were cultural experiences promoted by plants (27%) and other physical or psychological experiences (10%). Table 2 shows how the policy documents referred to the specific forest NCP whilst Appendix H shows in detail how the specific forest NCP contribute to each NCP group, material, regulating, and non-material.

3.2.2. Anthropogenic capitals

We found 1050 references to anthropogenic capitals in the policy documents. Human and social capitals were the anthropogenic capitals most commonly related to the co-production of forest NCP, appearing in 38% and 35% of the statements, respectively (Fig. 4B). Human capital was for example referred to as "knowledge transfer" EAFRD Funding Regulation (1305/2013/EU, paragraph 4) or labour in the form of "thinning and removal of oppressors" (Silviculuture Directive Brandenburg, 2004) (Table 3). Social capital included "forest management associations" (Federal Forest Law, 1975, §16) or formal institutions, such as "federal and state government agencies" (Federal Nature Conservation and Maintenance Law, 2009, §2.2). Physical and financial capitals were referred to in 13% and 14% of the statements, respectively (Fig. 4B). Physical capital was referred to as the use of horses to move timber (Management Plan Proratzer Moränenlandschaft, 2015, p.217) or forest roads used for "forest management and recreation of visitors" (Baden-Württemberg State Forest Law, 2019, §19.1). Human capitals were distributed evenly across the category: manual labour (37%), knowledge (35%), and skills (28%). Social capital was dominated by institutions, which made up 90% of mentions in this category, while networks only accounted for 10%. The physical capital category was split evenly between tools and machinery (53%) as well as infrastructure and built capital (47%). Direct payments (95%) were the most common financial capital linked to the co-production of forest NCP, while subsidies were only found in 7% of financial capital related mentions.

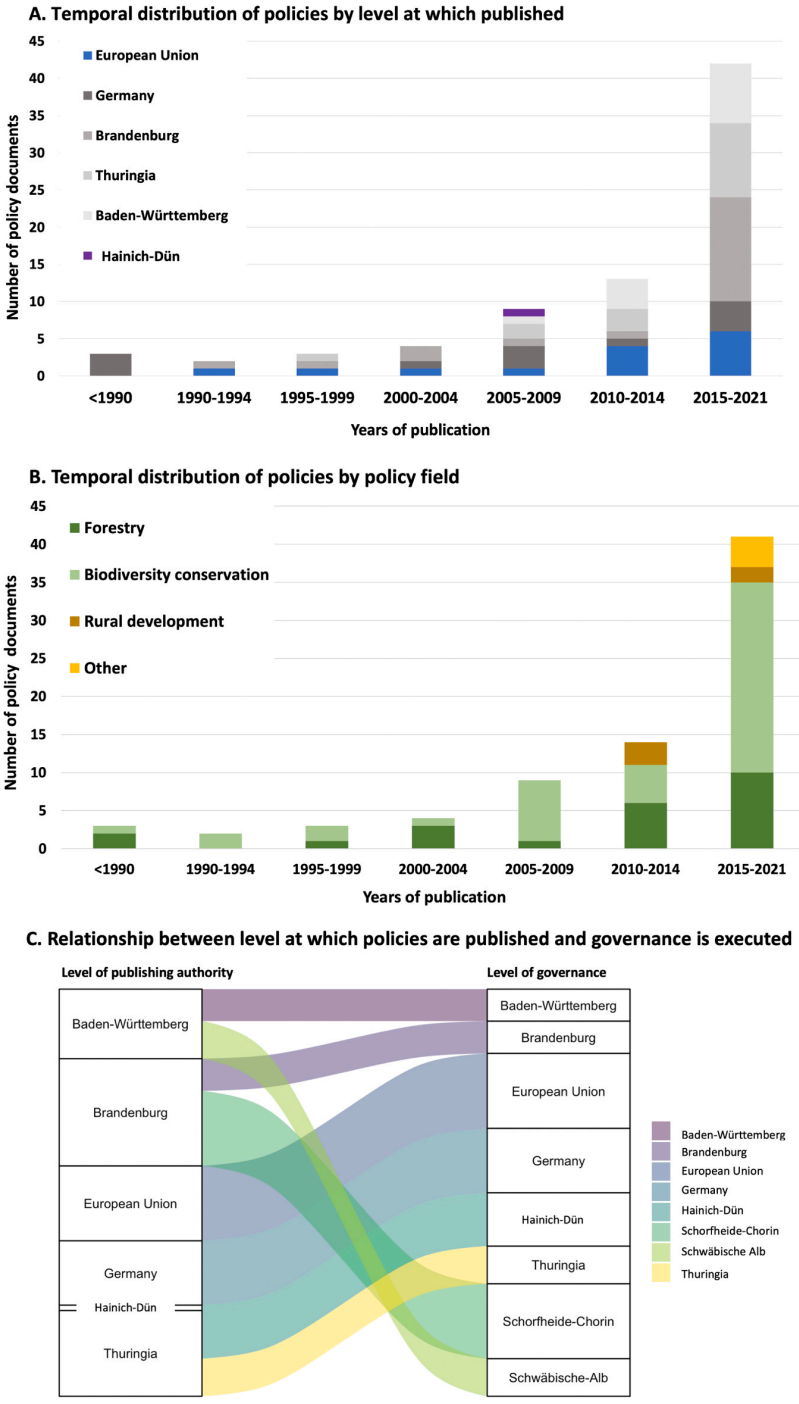

Fig. 3. A. Temporal distribution of analysed policy documents across governance levels at which these were published by years of publication (phases of five years). B. Temporal distribution of analysed policy documents by policy field. C. Alluvial diagram showing the governance level at which a policy document is published and which level it applies to. For example, the Regulation on the Biosphere Reserve Schorfheide-Chorin is authorised by the State of Brandenburg but only applies to the Schorfheide-Chorin area and not the entire state.

Table 3 shows how the policy documents referred to the specific anthropogenic capitals whilst Appendix I portrays in detail how individual anthropogenic capitals contributed to its overarching category namely human, social, physical, and financial capital.

3.2.3. *Governance modes*

The policy documents made to 711 statements concerning governance modes. Of these 60% were made to hierarchical governance shown for example in top-down regulation as in the Federal Forest Law (1975, §10.1), which states "initial afforestation of areas requires the approval of the authority responsible according to state law" (Fig. 4C).

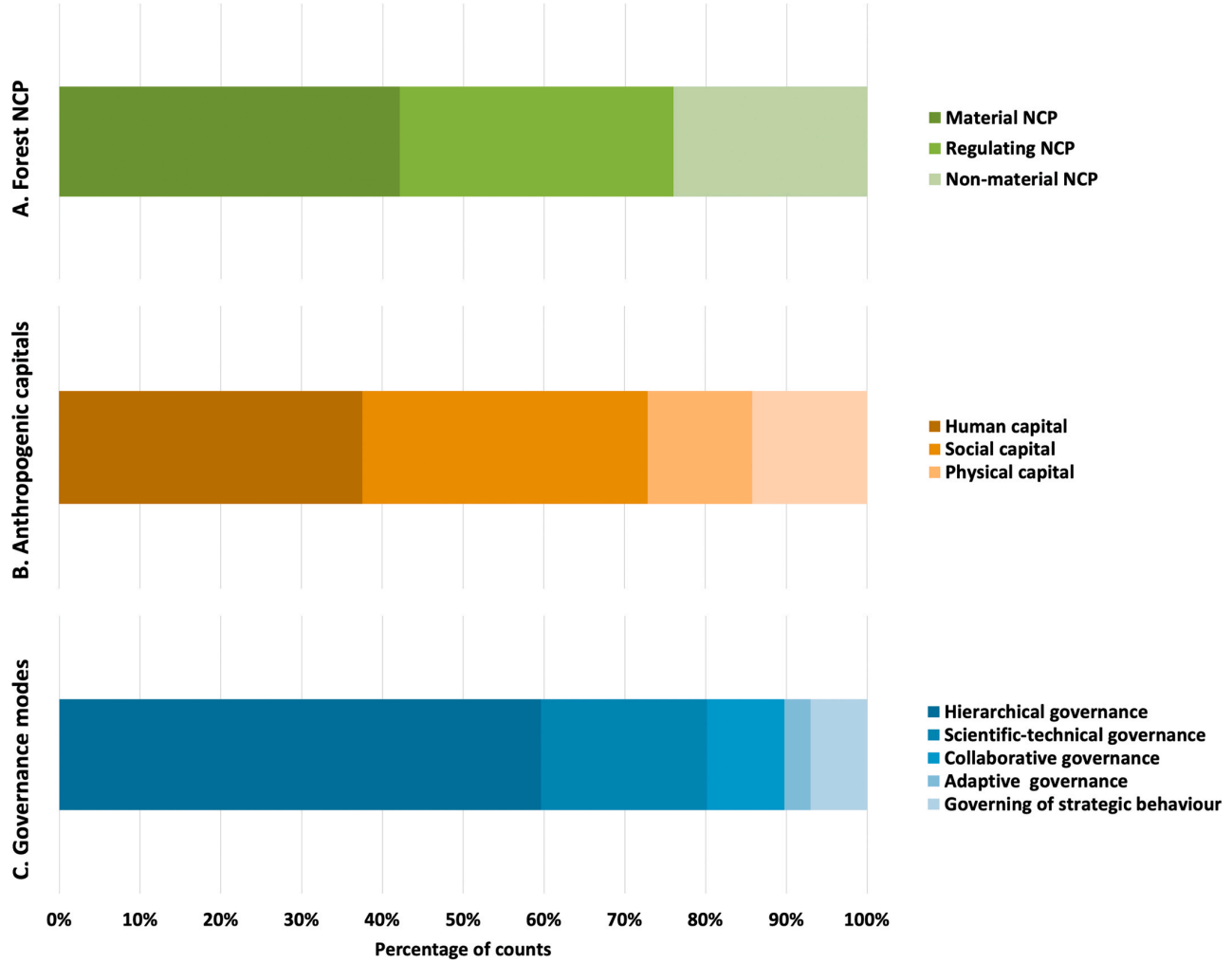

Fig. 4. Percentages of A. Co-produced nature's contributions to people (NCP) in forests, B. Anthropogenic capitals involved in the co-production of forest NCP, C. Governance modes affecting anthropogenic capitals in the co-production of forest NCP. Appendix H shows the focal NCP for each NCP category. Appendix I shows how individual anthropogenic capitals contribute to each capital category.

Scientific-technical governance was less common but remained vital as 20% of governance references were connected to this mode. The Directive on State-wide Forest Development Types in Baden-Württemberg (2014), for example, made technical requirements by defining the harvestable diameter of different tree species. Collaborative governance (10%), the governing of strategic behaviour (7%), and adaptive governance (3%) seemed to have minor influence (Fig. 4C). Collaborative governance was for example described regarding the creation and maintenance of habitats as "an intense collaboration between the forestry administration and the lower conservation agencies" (Technical Contribution Forests for the Natura 2000 Management Plan for Muschelkalkhänge von Großbartloff bis Faulungen and SPA Südliches Eichsfeld, 2014, p.3). The governing of strategic behaviour via direct payments, for example, was described in the Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021–2024, which lists financial contributions for a range of other anthropogenic capitals and forest NCP (2020, pp.96–113).

3.2.4. *Anthropogenic capitals contributing to forest NCP co-production*

The heatmap in Fig. 5 highlights to what degree anthropogenic capital contributed to the co-production of a specific forest NCP as stated by policy documents. Most statements in the policy documents referred to anthropogenic capitals involved in the co-production of timber. These capitals predominantly included institutions, skills, direct payments, and knowledge. Institutions were found to be contributing to most NCP, particularly to timber production, habitat creation, and bird watching. Direct payments were also important when referring to the governance of habitat creation and maintenance. A table showing the connections between NCP and capitals can be found in Appendix J.

3.3. *Co-production of forest NCP in policy documents across multiple governance levels*

We found that policy documents vary across governance levels in their focus regarding forest NCP, anthropogenic capitals, and modes of governance. Yet, it is crucial to bear in mind that policy documents at one governance level, may only apply to governing anthropogenic capitals and the forest NCP they co-produce at a subsidiary level. Overall, we found that material and regulating NCP were more frequently mentioned in the policy documents at the EU, national, and federal states level (Fig. 6). At the local level, non-material (46% of the statements) and material (36%) NCP were most prominently mentioned, while regulating NCP (18%) were referred to less often (Fig. 6). We found associations between the NCP categories and governance levels

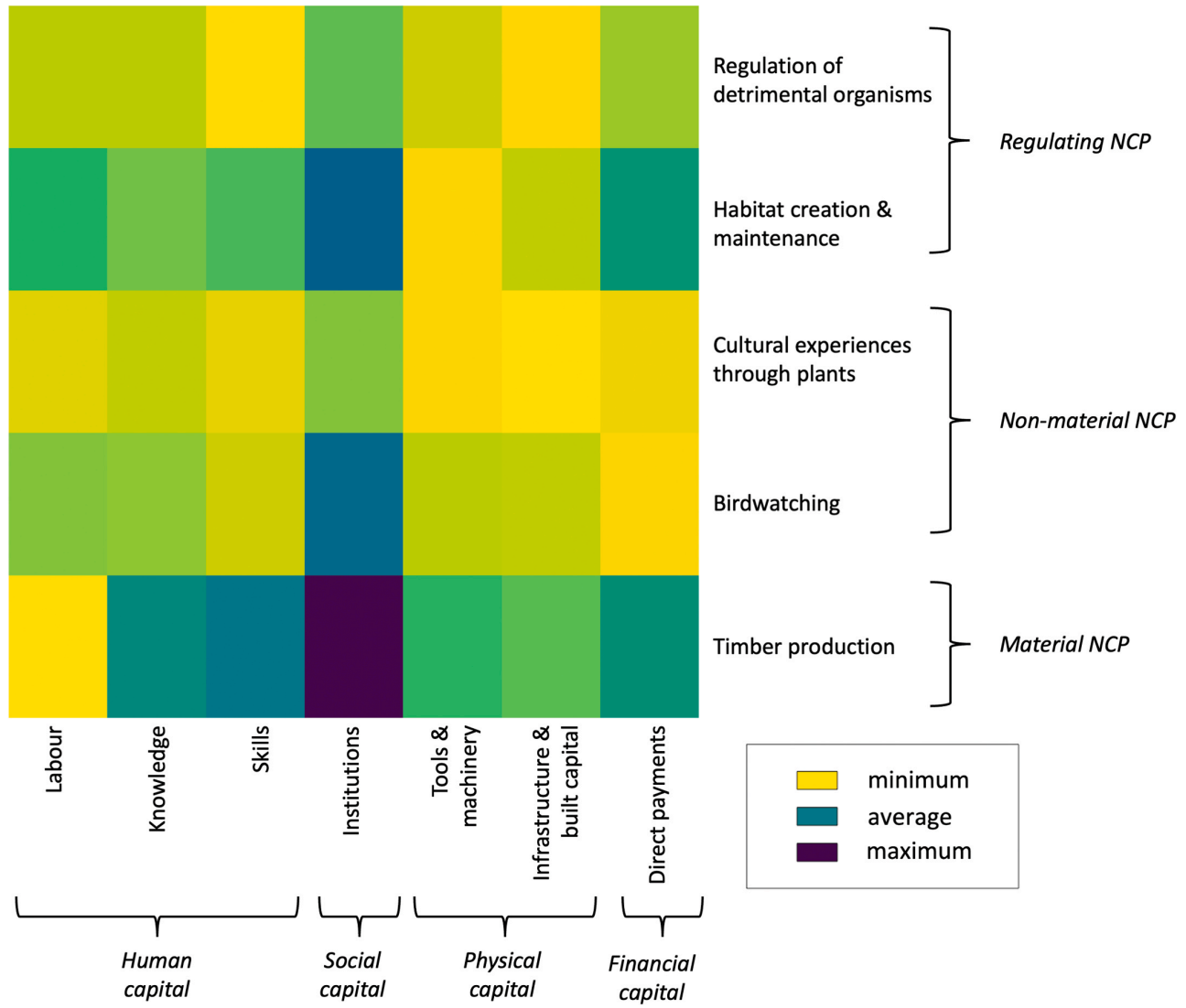

Fig. 5. Heatmap displaying the number of mentions of anthropogenic capitals contributing to the supply of nature's contributions to people (NCP) in forests. Few to no mentions in the policy documents are depicted in yellow, some in shades of green, and the maximum of mentions in dark purple. See Appendix J for the exact number of mentions in policy documents that refer to the management of each capital for every NCP shown in the heatmap.

($X^2 = 82.83$; df = 6; $p < 0.0001$): while non-material NCP were significantly more often stated at the local level, regulating NCP were more often mentioned at the national level (Appendix K).

Regarding anthropocentric capitals, we found a similar distribution of statements referring to the different capitals across governance levels. A higher proportion of statements referred to human and social capitals and a lower proportion to physical capital (Fig. 6). While we found that human capital was significantly more often mentioned at the EU level than in the other levels ($X^2 = 6.92$; df = 1; $p < 0.01$; Appendix K), financial capital was mentioned significantly more often at national and federal-state levels (Germany: $X^2 = 6.55$; df = 1; $p = 0.01$; federal states: $X^2 = 35.74$; df = 1; $p < 0.0001$; Appendix K) and physical capital was mentioned significantly more often at the local level ($X^2 = 4.25$; df = 1; $p = 0.039$; Appendix K).

Regarding governance modes, we found that the hierarchical mode was mentioned most frequently across governance levels (Fig. 6), although it presented a significant positive association with the federal ($X^2 = 23.26$; df = 1; $p < 0.0001$; Appendix K) and local level ($X^2 = 7.78$; df = 1; $p < 0.01$; Appendix K). Across governance levels, collaborative and adaptive governance modes are mentioned least frequently (Fig. 6). Governing of strategic behaviour was associated significantly with the EU and German/national levels (EU: $X^2 = 13.35$; df = 1; $p < 0.001$; Germany: $X^2 = 36.83$; df = 1; $p < 0.0001$; Appendix K) and was not found at the local level.

3.4. Governing the co-production of forest NCP: archetypes

The redundancy analysis (RDA) demonstrated a statistically significant relationship between forest NCP and the anthropogenic capitals contributing to their co-production, and the mode and level that is governing this relationship, unveiling six archetypes of governing anthropogenic capitals in the co-production of forest NCP (Monte Carlo permutation test; $p < 0.0001$). The RDA's first three axes showed an accumulated variance of 79.50% (Table 4).

The positive scores of the first axis (46.78% of the total variance) represented the association between two regulating NCP, i.e., habitat

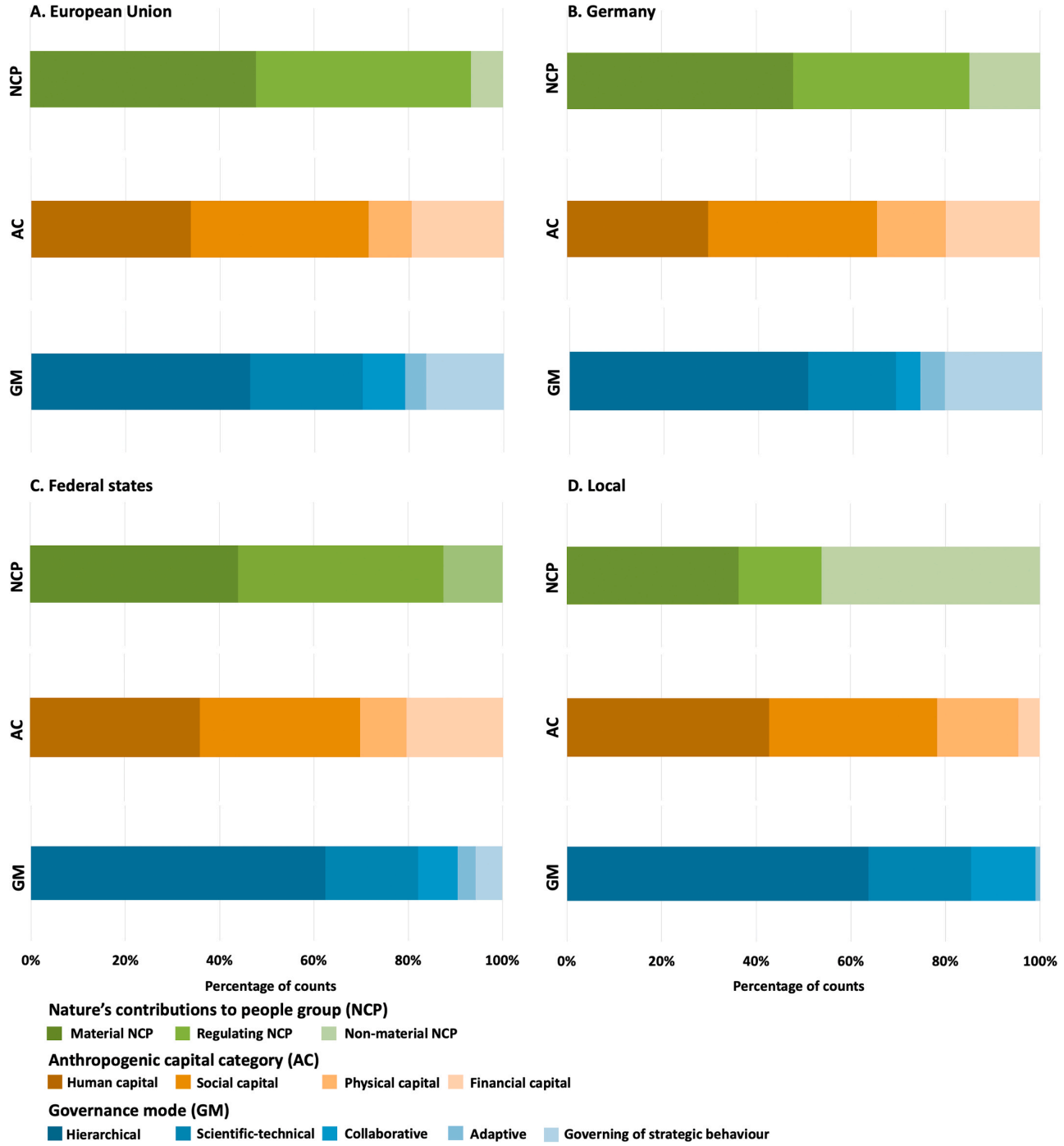

Fig. 6. Percentages of the distribution of nature's contributions to people (NCP) in forests by NCP group, the anthropogenic capitals (AC) contributing to their co-production, and the modes of governance (GM) affecting these, across governance levels: A. the European Union, B. Germany, C. the federal states (Brandenburg, Thuringia, and Baden-Württemberg), and D. the local case study level. For statistically significant associations between governance levels and NCP categories, anthropogenic capitals, and governance modes, see Appendix K.

creation and maintenance and regulation of hazards and extreme events, and the financial capital of direct payments. This association is explained by two governance modes, i.e., governing of strategic behaviour and adaptive governance, that are executed at the federal-state level. This relationship is referred to as *Archetype 1, "governing of strategic behaviour for regulating NCP"*. The negative scores of axis 1 represented *Archetype 2, "governing habitat management for experiences in nature"*. This archetype shows the association between knowledge and the non-material NCP of birdwatching and cultural experiences through plants, which is explained by scientific-technical governance executed locally (Table 4).

The second axis (20.10%) represented *Archetype 3, "governing habitat*

Table 4
Redundancy analysis (RDA) results for the three first factor axes. Scores of the variables and RDA statistics are presented. Bold values indicate the variables with the largest squared cosine in each axis, signifying those variables with higher representation for each axis.

Dependent variables		Axis 1	Axis 2	Axis 3
Nature's contributions to people in forests (NCP)				
Material NCP	Timber production	0.131	**-0.231**	-0.039
	Food	-0.036	0.003	0.017
Non-material NCP	Birdwatching	**-0.411**	0.310	0.155
	Cultural experiences through plants	-0.099	0.032	**0.101**
	Other physical or psychological experiences	-0.027	-0.052	-0.007
Regulating NCP	Habitat creation and maintenance	**0.235**	0.057	**-0.218**
	Regulation of climate	0.010	-0.126	0.046
	Regulation of detrimental organisms	0.097	0.070	-0.075
	Regulation of hazards and extreme events	**0.076**	-0.040	-0.001
	Soil formation and protection	0.020	-0.004	-0.001
Anthropogenic capitals				
Human capital	Labour	0.047	**0.355**	0.111
	Knowledge	-0.129	-0.117	-0.017
	Skills	-0.031	-0.196	-0.211
Social capital	Networks	-0.042	**-0.269**	0.045
	Institutions	0.010	**0.404**	**-0.407**
Physical capital	Tools and machinery	0.020	**0.207**	**0.235**
	Infrastructure and built capital	0.055	-0.005	**0.138**
Financial capital	Direct payments	**1.095**	0.079	0.106
	Subsidies	-0.016	-0.002	-0.040
Independent variables				
Governance levels	European Union	0.025	**-0.178**	0.041
	Germany	0.068	-0.070	0.035
	Federal state	**0.362**	0.075	**-0.193**
	Local	**-0.441**	**0.076**	**0.152**
Governance modes	Hierarchical governance	0.086	**0.323**	-0.024
	Scientific-technical governance	-0.086	-0.040	**-0.274**
	Collaborative governance	0.011	-0.136	-0.003
	Adaptive governance	0.171	0.013	-0.114
	Governing of strategic behaviour	**0.492**	-0.008	**0.150**
RDA statistics				
	Eigenvalue	0.093	0.040	0.025
	Explained variance (%)	46.775	20.101	12.627
	% Accumulated variance	46.775	66.877	79.504

management for pest control" in its positive scores, and *Archetype 4, "collaborative governance for timber"* in its negative scores (Table 4). *Archetype 3* described the contributions of labour, institutions, and tools and machinery to two regulating NCP, i.e. regulation of detrimental organisms and habitat creation and maintenance. These were governed hierarchically at the local and federal-state levels. *Archetype 4* highlighted the importance of social networks, skills, and knowledge for timber production and the regulation of climate. This relationship is explained by collaborative governance at the national and EU levels.

The third axis (12.63%) represented *Archetype 5, "local governance for experiences in nature"* in its positive scores and *Archetype 6, "promoting knowledge for habitat protection"* (Table 4). *Archetype 5* indicates the association between the use of tools and machinery as well as infrastructure and built capitals and the NCP birdwatching and cultural experiences through plants, all of which were influenced by the local level. *Archetype 6* shows the influence of scientific-technical governance at the federal-state level to two regulating NCP, i.e., habitat creation and maintenance and regulation of detrimental organisms, which co-production required skills and institutions.

The ANOVA tests performed with the RDA axes revealed different archetypes across the Biodiversity Exploratories (Table 5). Specifically, the negative scores of RDA axis 1 (*Archetype 2*) were significantly lower

Table 5
Mean values and statistical differences of the three RDA axes between the Biodiversity Exploratories: Schorfheide-Chorin, Hainich-Dün, and Schwäbische Alb. Mean values with different letters (a, b) indicate significant differences from one another based on the pairwise comparison t-test with Bonferroni correction ($p < 0.01$).

RDA axis	Schorfheide-Chorin	Hainich-Dün	Schwäbische Alb	F value	P value
Axis 1	-0.304^{b}	-0.343^{b}	-0.045^{a}	29.19	< 0.0001
Axis 2	0.265^{a}	$0.082^{a,b}$	-0.287^{b}	10.56	< 0.0001
Axis 3	0.312^{a}	$0.151^{a,b}$	-0.164^{b}	10.77	< 0.0001

in Schorfheide-Chorin and Hainich-Dün, the positive scores of RDA axes 2 and 3 (*Archetypes 3* and *5*, respectively) were significantly higher in Schorfheide-Chorin. The negative scores of Axes 2 and 3 (*Archetypes 4* and *6*, respectively) were significantly lower in the Schwäbische Alb.

4. Discussion

4.1. Governing anthropogenic capitals in the co-production of forest NCP

This document analysis investigated how 76 forest-related policy documents consider the different modes of governance influencing anthropogenic capitals in the co-production of forest NCP. In line with Primmer et al. (2021), we included documents from several policy fields, including forestry, biodiversity conservation, and rural development. Our analysis showed that forest-related policy documents do not explicitly address NCP co-production. Nonetheless, anthropogenic capitals are considered by policymakers across governance levels when designing policy to govern forests and the contributions they provide to human wellbeing.

First, our analysis revealed that material NCP were referred to most often by the policy documents, closely followed by regulating NCP. At the same time, non-material NCP were only found in one-quarter of mentions. This pattern also applies when assessing policy documents across governance levels (Fig. 6). Our results are in line with the findings by Primmer et al. (2021) when focussing on specific NCP. Timber production as well as the creation and maintenance of habitats were referred to most often, while non-material NCP, such as birdwatching, were less prominent in the policy documents reviewed. Timber production, for example, is described as a primary goal of continuous forest management focussing on the "harvest of valuable, harvestable trees according to quality and a defined diameter" (Directive on State-wide Forest Development Types Baden-Württemberg, 2014, pp.4–5). Similarly, the Brandenburg Silviculture Directive (2014) highlights the importance of forest management for the creation and management of habitat by noting that "micro-structures in forests, such as wet spots, rocks, boulders, etc. are to be preserved, protected, and eventually promoted. They serve as habitat in the sense of providing micro-habitats or micro-biotopes." (p.4). The importance of forests as providers of non-material NCP is recognised by the German Forest Strategy 2020 (2011), for example, which points out that "forests play an important role for physical and psychological regeneration of people and are intensively used for recreation, leisure activities, and sports, particularly in conurbation and outer conurbation areas." (p.29). Thus, the reviewed policy documents recognise the multifunctionality of forests and the influence that management has on the provision of the various NCP illustrated above.

Second, our analysis revealed that, overall and across governance levels, human and social capitals are dominant. Human and social capital also interact as the Directive on state-wide Forest Development Types Baden-Württemberg (2014, p.3) illustrates by referring to the sharing of forest-related skills in silvicultural programmes to "enable forester owners to achieve their operational goals". In contrast, our findings show that physical and financial capitals play a less critical role.

Physical capital, for example, is described as prerequisite for obtaining forest NCP by the Baden-Württemberg State Forest Law (2019, §19.1): "Forest roads serve the forest development of forest management and recreation of visitors". Financial capital on the other hand is described as a supportive capital to ensure forest multifunctionality. The Federal Forest Law of Germany (1975, §41.1), for example, illustrates this by stating "the forestry sector is to be financially supported by the state for the productive, protective, and social function of forests (…)".

The interplay of various anthropogenic capitals in the co-production of forest NCP is also highlighted by our heatmap (Fig. 5), as it shows that timber production, for example, depends on the interplay of natural capital with institutions, forestry related skills and knowledge, as well as direct payments. The Thuringia Directive on Forestry Measures (2014, p.5) refers to this interplay by stating that direct payments target "the improvement of forestry infrastructure to make insufficiently developed forests accessible for a sustainable use and management, the prevention of prevent damage, and for recreational needs of the general public". Surprisingly, and despite the importance of machinery for timber harvests, relatively few mentions were made to physical capital. Similarly, the limited number of statements referring to the governance of financial capital deviated from our expectations since subsidies have been described as a vital instrument to steer forest production by the scientific literature (Sotirov and Storch, 2018).

Third, our analysis showed that governance of anthropogenic capitals in NCP co-production is predominantly hierarchical, although most levels, except the local, show all modes of governance (Fig. 6). Yet, the hierarchical governance at the local and federal-state levels defines the governance *archetype 3, "governing habitat management for pest control"* (Table 4). Overall, our results affirm Primmer et al. (2015) who pointed out that hierarchical governance influences other modes of governance. However, further research needs to investigate how these modes are interlinked in governing anthropogenic capitals in NCP co-production.

4.2. Governing anthropogenic capitals across multiple levels

Our analysis showed that policy documents across governance levels recognise anthropogenic capitals involved in the co-production of forest NCP, but predominantly influence them through hierarchical and scientific-technical governance. These findings support the notion that forest governance in the EU is polycentric as the member states and authorities on several subordinate levels affect it (Lazdinis et al., 2019). The European Commission recognises this polycentricity by referring to the essential involvement of member states and a variety of actors in the EU Forest Strategy (COM 2021/572, p.3): "All the measures are to be designed and implemented in close cooperation with the Member States as well as public and private forest owners and other caretakers of forests, (…). The Strategy seeks the active engagement of all relevant actors and levels of governance, from Member States to forest owners and managers, forest-based industries, scientists, civil society, and other stakeholders."

Despite the recognition of this polycentrism, we found that governance levels recognise anthropogenic capitals and the NCP they co-produce differently. Similarly to previous analyses, our results showed that forest-related policy documents at the EU level cover several material, non-material, and regulating NCP (e.g., Bouwma et al., 2018; Elomina and Pülzl, 2021; Primmer et al., 2021). In slight contrast to Bouwma et al. (2018) who identified regulating NCP as most prominent NCP in EU policies, our analysis found most co-produced forest NCP to be material and regulating. Thus, our findings align with Elomina and Pülzl (2021) who found material NCP most represented across policies and policy domains. The EU Forest Strategy 2030 (2021), for example, acknowledges the importance of wood and non-wood material forest NCP when highlighting that in "2018, in the EU, 2,1 million people were working in the traditional forest-based sector" (p.4) whilst also stressing that "EU forests provide highly valuable non-wood products, such as cork (80% of the worldwide production), resin, tannins, fodder, medicinal and aromatic plants, fruits, berries, nuts, roots, mushrooms, seeds, honey, ornamentals and wild game, which often benefit the local communities" (p.8). The EU Forest Strategy 2030, thus, explicitly recognises the value non-wood forest products provide to people across Europe, particularly in Eastern European countries (Lovrić et al., 2020). Besides, our analysis revealed that governance modes at the EU level are linked to specific anthropogenic capitals and the NCP they co-produce. Human capital in the form of knowledge, for example, is very important in EU policy documents due to the role of scientific-technical governance in the Habitats Directive (92/43/EWG) and the Birds Directive (2009/147/EC) for Natura 2000 sites. The Birds Directive, for example, emphasises the role of science in knowledge generation by stating that the "conservation of birds and, in particular, migratory birds still presents problems which call for scientific research. Such research will also make it possible to assess the effectiveness of the measures taken" (2009, paragraph 13). Similarly to human capital being influenced by scientific-technical governance, financial capital is steered by the governing of strategic behaviour as EU funds are allocated within the CAP or the Habitats Directive for Natura 2000 sites (Winkel et al., 2013). Indeed, the governance of the regulating NCP -habitat creation and maintenance- through shaping behaviours with subsidies and direct payments conforms the governance archetype *governing of strategic behaviour for regulating NCP* (Fig. 7).

The German national level showed similar characteristics to the EU level as material NCP were most often referred to. Despite German forest law being strongly focussed on timber production (Sotirov and Storch, 2018), our analysis showed that forest-related policy documents also promote regulating NCP. The German Forest Strategy 2050, for example, not only highlights forest's capacity to sequester carbon via long-term wood uses in building materials or furniture (p.20) but refers to the importance of air and water filtration through forests (pp.38–40). Besides, the policy documents at the German level only referred to few non-material NCP, which was surprising given that recreation in forests is important to the general public and access to forests for recreational purposes is a given right across Germany (Hochmalová et al., 2021). Whilst the German Federal Forest Law (1975, §13) simply refers to the term *Erholungswald* (recreation forest), the German Forest Strategy 2050 (2021, pp. 34–35) is much more specific by listing a broad range of non-material forest NCP and referring to the need of collaboration among actors involved in the provision of these. Moreover, the importance of social and human capital at the national level can be attributed to the steering of subsidiary levels through laws and regulations and the integration of scientific knowledge in conservation related policy documents (Sutherland et al., 2004). Like the EU in the CAP, the German national government allocates financial capital to support the provision of NCP (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2022). The use of these capitals resembles the modes of governing forest NCP at the national level. Here, our results correspond with the findings by Juerges et al. (2020), who identified German forest governance to be mainly coercive (hierarchical governance). Nonetheless, German forest governance employs monetary incentives (governing of strategic behaviour) and information, e.g., expert knowledge (scientific-technical governance), to promote specific forest NCP (ibid.).

Policy documents on the federal-state level resemble those on the national level regarding the co-production of forest NCP. This finding is unsurprising as forest governance is split between the German national level (*Bundesrepublik*) and 16 federal states (*Bundesländer*) (Lazdinis et al., 2019). The federal states hold strong competencies regarding the governance of forests due to their partial autonomy in Germany's federal system, despite the obligation to adapt national forestry and conservation legislation into federal-state law (Grotz, 2012; Rehbinder, 2019). Besides, owning large parts of forests on their territory provides the federal states with strong influence over forests and the anthropogenic capitals used to co-produce NCP. However, the federal states are obliged by law to manage their forests to serve public welfare and provide multiple NCP (Rehbinder, 2019). The Directive on State-wide

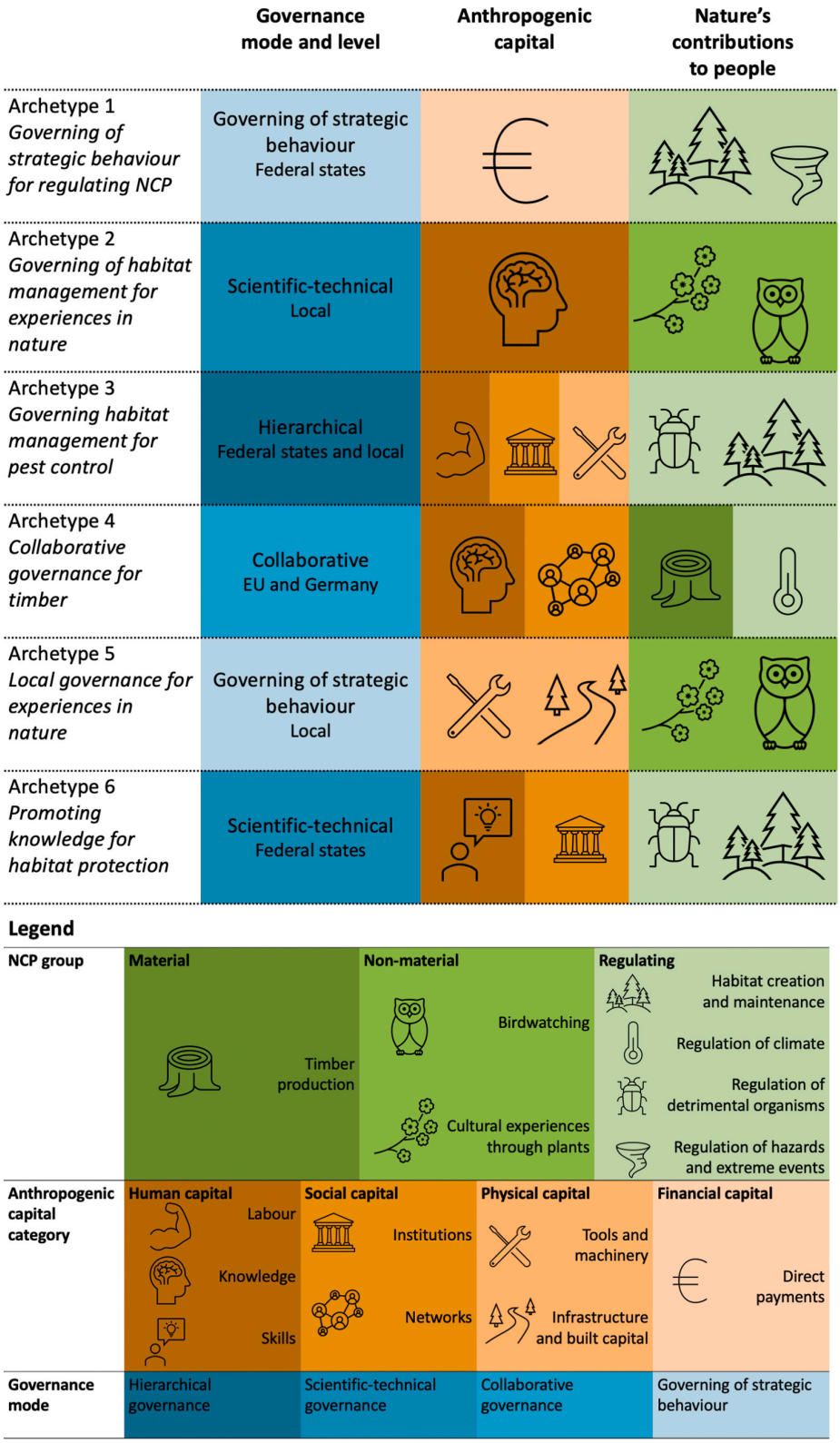

Fig. 7. Six archetypes of governing the co-production of forest NCP. Archetypes are connected to the level at which they are governed by policies (own illustration).

Forest Development Types for the Baden-Württemberg illustrates this goal by highlighting that "an integrative, multifunctional, (and) welfare-focussed management of public forests has proven to be the way to go considering the current circumstances" (2014, p.2).

In contrast, policy documents on the local case study level mostly referred to non-material NCP, comprising the governance archetypes *governing habitat management for experiences in nature* and *local governance for experiences in nature* (Fig. 7). This can be ascribed to the importance of recreational activities and tourism in the management plans for Biosphere Reserves and national parks. The Framework Concept Volume 3: Our Way (2012) for the Biosphere Reserve Schwäbische Alb illustrates the challenge of protecting habitats whilst allowing for recreational activities when stating that the Biosphere Reserve "should be recognisable to locals and visitors in the cultural landscape that is well worth protecting. Those areas endangered by the immense pressure through visitors need to be protected in particular but remain enjoyable for visitors" (p.106). Besides, various studies, including several on the Biosphere Reserve Schwäbische Alb, have shown that non-material NCP such as recreation, sense of place, or aesthetic values are integral to Biosphere Reserves (Bieling, 2014; Müller et al., 2019; Plieninger et al., 2013). Despite strong similarities between the local and superior levels regarding most anthropogenic capitals and modes of governance, we found few references to financial capital and governing of strategic behaviour was found in policy documents at the local level. This is unsurprising since most funding used to co-produce forest NCP is provided by the EU and the national level whilst being distributed via the federal states (Graf et al., 2022), for example via the Directive on Subsidies for Nature Protection Measures in Forests and Measures to address the Effects of Extreme Weather Events (2021) in the state of Brandenburg which is based on various EU regulations (e.g., 2013/1303/EU, 2013/1305/EU) and national legislation, such as the Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection. Besides, we found few mentions to adaptive governance on the local level. While several studies have demonstrated that adaptive governance or adaptive (co-) management is what characterises Biosphere Reserves, this was not reflected in the policy documents analysed (e.g., Baird et al., 2018; Olsson et al., 2007; Schultz et al., 2011). This may be since "UNESCO Man and Biosphere Reserves are often governed by an informal ad hoc assembly of concerned individuals and NGOs with no legal power but the ability to influence the policy-making process" as Folke et al., (2005, p. 451) pointed out. Hence, the adaptive nature of governing Biosphere Reserves does not explicitly appear in the policy documents regarding forest NCP management.

4.3. Six archetypes of governing anthropogenic capitals in the co-production of forest NCP

The performed redundancy analysis uncovered six archetypes that characterise how, and at which level the policy documents intend to govern the anthropogenic capitals co-producing forest NCP (Fig. 7). Yet, the performed ANOVA tests revealed that the archetypes also varied across the three case study sites (Table 5).

Archetype 1 encompasses the *governing of strategic behaviour for regulating NCP* as it describes how direct payments are allocated by the federal states via the governing of strategic behaviour to support habitat creation and maintenance and the regulation of hazards. This archetype thus relates to the public funding for biodiversity conservation in Natura 2000 sites as described in various studies (e.g., Geitzenauer et al., 2017; Sarvašová et al., 2019; Wätzold et al., 2010; Winkel et al., 2015). Most funding for Natura 2000 sites is derived from EAFRD and the EU's LIFE Nature programme and managed by EU member states and their subsidiary entities, for example federal states in Germany (Geitzenauer et al., 2017; Winkel et al., 2015). In addition, this archetype also describes the implementation of payments for ecosystem services to support and restore forest NCP as requested by the EU Forest Strategy, the Bioeconomy Strategy, and the Biodiversity Strategy (Viszlai et al., 2016).

Archetype 2, governing habitat management for experiences in nature, illustrates how Natura 2000 management plans contribute to the knowledge on habitats and species for birdwatching and cultural experiences with plants. Kordowska (2017) provides an example for this archetype when referring to the birdwatching potential in Natura 2000 sites in Poland. Besides, managed forests also provide a great diversity of edible plants (Pohjanmies et al., 2021). These support recreational activities, for example, by providing touristic activities for mushroom foraging (Balachander et al., 2022). This archetype was dominant in the Biosphere Reserve Schwäbische Alb, but less so in the Biosphere Reserve Schorfheide-Chorin and the case study Hainich-Dün. This can be ascribed to the Biosphere Reserve administration's goal to promote recreational activities in the region whilst protecting the cultural landscape (Biosphere Reserve Schwäbische Alb Framework Concept Volume 3: Our Way, 2012).

Archetype 3, governing habitat management for pest control, refers to the management of pest control through manual labour and tools to create healthy forests. An example for this archetype is the mechanical treatment of bark-beetle-infested trees. While debarking trees is widely used, especially in protected areas, bark scratching or gouging with specific machinery has been described as a more efficient pest control method with reduced negative effects on forest biodiversity (Hagge et al., 2019; Thorn et al., 2016).

Archetype 4, collaborative governance for timber production, refers to the steering of forest management that relies on social networks to share knowledge and skills. Specifically, this archetype represents forestry associations that organise timber production and selling (Korhonen et al., 2012; Schraml, 2005). This archetype was, for example, dominant in the Hainich-Dün case study which can be attributed to the various forest cooperatives that have managed forests in the area for centuries (Hessenmöller et al., 2018). Besides, collaborative efforts between forestry administrations and lower conservation agencies were mentioned explicitly in the Technical Contributions on Forests within this case study. In contrast, this archetype was less dominant in the Biosphere Reserve Schwäbische-Alb, which may be due to the strong focus on conservation and tourism within the Biosphere Reserve (Biosphere Reserve Schwäbische Alb Framework Concept Volume 1–3, 2012).

Archetype 5, local governance for experiences in nature, describes how tools and infrastructure are governed locally to provide people access to nature. This archetype was found across both Biosphere Reserves and the National Park, which all promote recreational activities in their respective areas (Biosphere Reserve Schwäbische Alb Framework Concepts Volumes 1–3, 2012; Maintenance and Development Plan for the Biosphere Reserve Schorfheide-Chorin, 1997; National Park Plan for the National Park Hainich, 2007). However, this archetype was dominant in the Biosphere Reserve Schwäbische-Alb, which is home to a cultural landscape important to locals and visitors alike (Bieling, 2014; Müller et al., 2019; Plieninger et al., 2013). Our findings thus align with recent literature, which has shown that the management of infrastructure, such as roads or hiking paths, has proven to be essential for recreational experiences in Biosphere Reserves (Palliwoda et al., 2021) and national parks (Schägner et al., 2016).

Archetype 6 is based on the notion that Natura 2000 management plans are used to promote *knowledge and skills for habitat protection through scientific-technical governance*. This archetype was less dominant in the Biosphere Reserve Schwäbische Alb in comparison to the other two case study sites due to fewer Natura 2000 sites in the area. For Schwäbische Alb we only identified three Natura 2000 sites that included plots of the Biodiversity Exploratories, whilst we identified six for Hainich-Dün and eleven for Schorfheide-Chorin. Despite this imbalance, it can be noted that Natura 2000 management plans play an increasingly important role in protecting habitats (Winter et al., 2014). However, little knowledge is transferred to forest owners and managers

from these management plans (ibid.). This discrepancy illustrates that the intention of policy documents and the actual management of ecosystems do not always align.

The six archetypes reveal that the reviewed policy documents especially aim to promote the creation and maintenance of habitat by focussing on different anthropogenic capitals, such as direct payments (*Archetype 1*), machinery and skills (*Archetype 3*), or knowledge (*Archetype 6*). Besides, the archetypes show that policy documents aim to generate synergies between the protection of habitat and the ways people can obtain non-material NCP in forests (*Archetypes 2 & 5*). Thus, the policy documents are in line with the aim of Biosphere Reserves allowing for strict conservation in their core zones whilst allowing for recreational activities in the buffer and transition zones (Reed, 2020). Similarly, *Archetype 4* revealed that the policy documents promote synergies between material NCP, namely timber production, and the regulation of climate by promoting collaborative efforts in forest management, but neglect other anthropogenic capitals involved in this co-production. Thus, the archetypes reveal that the policy documents account for the multifunctionality of forests by recognising that synergies between different NCP can be fostered depending on which and how anthropogenic capitals are promoted.

5. Conclusion

Forests are multifunctional and support human wellbeing with multiple nature's contributions to people. These are co-produced by an interplay of nature with several anthropogenic capitals and governed across multiple levels. We conducted a policy document analysis to understand how anthropogenic capitals in the co-production of forest NCP are formally governed across these levels ranging from the local case study level to the EU. We focussed on three case study sites across Germany, two Biosphere Reserves and one containing a national park. Our analysis revealed that policy documents acknowledge the role of anthropogenic capitals in the provision of forest NCP despite not referring to the term co-production explicitly. The policy documents predominantly refer to material and regulating NCP as well as human and social capitals, which they intend to govern via hierarchical and scientific-technical governance across governance levels. Our analysis showed that the policy documents mainly referred to the role of institutions in the co-production of forest NCP, especially timber production. Similarly, the policy documents referred to knowledge, skills and direct payments as important capitals in the co-production of forest NCP.

Moreover, our analysis revealed six archetypes of governing the co-production of forest NCP: *Archetype 1 "the governing of strategic behaviour for regulating NCP"*, *Archetype 2 "governing habitat management for experiences in nature"*, *Archetype 3 "governing habitat management for pest control"*, *Archetype 4 "collaborative governance for timber"*, *Archetype 5 "local governance for experiences in nature"*, and *Archetype 6 "promoting knowledge for habitat protection"*. These archetypes represent six different governance modes operating at a particular governance level and fostering specific anthropogenic capitals for one or more forest NCP. Besides, the archetypes reveal that policy documents aim to create synergies between forest NCP belonging to different NCP groups, for example by allowing for recreational activities whilst creating and managing habitats. Decision-makers can profit of this knowledge when designing new policy by acknowledging that the favouring of specific anthropogenic capitals in the co-production of forest NCP can promote potential synergies. Nonetheless, further research needs investigate which combinations of anthropogenic capitals contribute to these synergies to determine co-production of forest NCP can be made more sustainable.

CRediT authorship contribution statement

- We have no no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- We have not submitted nor published the manuscript nor parts of it elsewhere.
- We have not used any AI or AI based technologies in the preparation of this manuscript.

Declaration of Competing Interest

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

Data Availability

This work is based on data elaborated by ESuDis of the Biodiversity Exploratories program (DFG Priority Program 1374). The datasets are publicly available in the Biodiversity Exploratories Information System (http://doi.org/10.17616/R32P9Q), (Dataset 31234). Biodiversity Exploratories Information System (BExIS), 2022. Borders of all three exploratory regions [Dataset 31234]. Borders of all three exploratory regions. URL https://www.bexis.uni-jena.de (accessed 11.29.22).

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Author contributions

Conceptualisation: BML, RI. Paper writing: RI, CS, BML, JH, JK. Policy coding: LSD, JH, JK, RI. Data analysis: BML, RI

Disclosure statement

No potential conflict of interest was reported by the authors.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2023.103657.

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Chapter IV

The forest beyond the trees: a network perspective on governing nature's contributions to people co-production

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in preparation

The forest beyond the trees: a network perspective on governing nature's contributions to people co-production

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Abstract

1. Forests provide multiple nature's contributions to people (NCP) that are co-produced by an interplay of natural and anthropogenic capitals, including human, social, physical, and financial capital. Like forests and NCP, anthropogenic capitals are governed by various actors across levels. Although forest governance research has explored the relationships of these actors to NCP co-production using social network analysis, it remains unclear how the relationships between actors influence the governance of anthropogenic capitals in the co-production of forest NCP.
2. We addressed this gap by focusing on the co-production of four forest NCP: timber, habitat creation and maintenance, climate regulation, and non-material NCP. Specifically, we aimed to (1) understand which actors are the most relevant in the management of different anthropogenic capitals involved in the co-production of these NCP, and (2) identify patterns of governing co-produced forest NCP via actor interactions based on the use of anthropogenic capitals. To do so, we conducted social network analyses based on interviews with local forest actors to reveal whom they perceived as the most influential actors in the management of anthropogenic capitals underpinning forest NCP.
3. Our findings show that timber production, climate regulation, and non-material NCP depend on few actors governing anthropogenic capitals (mainly knowledge and labour, financial capital, and infrastructure), while the creation and maintenance of habitat is influenced by a range of different actors using a variety of capitals. We identified three bundles of actors, anthropogenic capitals, and forest NCP that exemplify how these are governed: (*1) governance of timber production via financial flows*, (*2) governing knowledge and labour for climate regulation,* and *(3) governance for habitat management*.
4. Our analysis illustrates how specific actors drive the use and management of certain anthropogenic capitals in the co-production of forest NCP. Making these actor and capital

relationships tangible provides evidence of how certain anthropogenic capitals are favoured by specific actors and thus can inform decision-making to foster more sustainable forms of NCP co-production.

KEYWORDS
anthropogenic assets, ecosystem services coproduction, forest, governance, sustainable management

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1 INTRODUCTION

Forests provide multiple material, non-material, and regulating nature's contributions to people (NCP) including timber, food, carbon sequestration, water regulation, and recreation (Díaz et al., 2018; Felipe-Lucia et al., 2018; Teben'kova et al., 2020). These NCP are provided by an interplay between forests and humans in a process known as co-production, whereby people modify and manage forests to supply NCP and forests respond to the actions of humans through ecological dynamics such as recolonisation and succession (Bruley et al., 2021; Reyers et al., 2013; Spangenberg et al., 2014). Lavorel et al. (2020, p. 3) define co-production as the "emergence of benefits from nature to people through multiple, long-term and dynamic social interactions and the associated interplay of natural and human-derived capitals". Thus, in addition to its ecological elements, co-production relies on various anthropogenic capitals: human, social, physical and financial (Kachler et al., 2023b; Palomo et al., 2016). In a forest context, human capital refers to knowledge and skills within forest management practices or manual labour needed to harvest timber. Social capital encompasses rules and norms, for example, forest certifications or protected areas. Physical capital includes machinery and tools, such as chainsaws, harvesters, or forwarders, as well as infrastructure, such as skid roads. Financial capital refers to all monetary stocks and flows, including governmental direct payments, loans, or savings (Isaac et al., 2024; Palomo et al., 2016). S1 provides detailed definitions and forest-related examples of the four anthropogenic capital categories.

Recent studies have applied the co-production concept across various ecosystems (e.g., Grosinger et al., 2021; Kachler et al., 2023b; Lavorel et al., 2020), including forests (e.g., Bruley et al., 2021; Palliwoda et al., 2021; Torralba et al., 2018). Improved management

approaches to the co-production of forest NCP materialise in various forms. For example, timber may be harvested using suitable machinery or tools (Fischer and Eastwood, 2016); agroforestry practices can support micro-climate regulation by increasing shade via tree cover expansion (Lavorel et al., 2020); and pruning and tree lopping, which are based on the use of tools and manual labour, can not only lead to more expansive tree cover but may boost acorn production, a fruit traditionally used as fodder in the Mediterranean region (Garrido et al., 2017). Manual labour, knowledge, and husbandry skills can co-produce various regulating NCP through locally adapted forest management. For example, afforestation of high-alpine slopes may mitigate the risk of avalanches and create habitat for species (Bruley et al., 2021); and traditional burning practices in Australian woodlands can reduce the likelihood of destructive hot fires (Yibarbuk et al., 2001). Understanding how anthropogenic capitals are used to co-produce NCP is crucial for management when deciding whether substituting or complementing natural capital with anthropogenic capital will lead to an ideally sustainable provision of the NCP (Rieb et al., 2023).

Similarly, forest management decisions underpin which NCP are prioritised. For example, multi-functional, integrated, or multi-objective driven forest management supports the provision of multiple forest NCP, while intensive forestry management approaches focus solely on the production of timber (Borrass et al., 2017; Pukkala, 2016). Decisions about how to manage forests, which NCP are fostered, and which anthropogenic capitals are mobilised rely on processes established by diverse actors in formal and informal, often polycentric, governance settings across multiple levels (e.g., Arts, 2021; Mann et al., 2022; Primmer et al., 2021; Pülzl et al., 2013). Forest governance typically includes “network-like arrangements of public and private actors, self-regulation by market organisations, public-private partnerships, emission trading schemes, covenants, certification programs, etc.” (Arts and Buizer, 2009, p. 344). Thus, actor relationships in formal and informal networks can shape how forests and their contributions to people are managed (e.g., Górriz-Mifsud et al., 2017; Keskitalo et al., 2014; Korhonen et al., 2012; Schulz et al., 2018). For example, in Switzerland, although forest policy-making is mainly driven by a small network of expert knowledge holders, Schulz et al. (2018) demonstrated a significant effect of networks of non-governmental organisations (NGOs) on forest policy. Moreover, trust and exchanges of information fostered by actor networks are enabling factors for collaboration when governing forests and their NCP across governance levels, from local to international, and across sectors,

e.g., forest industry, tourism, or conservation (Borg et al., 2015; Keskitalo et al., 2014; Stoettner and Ní Dhubháin, 2019). Despite the relevant role of actor networks in shaping governance processes of forests and the NCP provided, the study of social network effects on the governance of NCP co-production remains underexplored.

Previously, the influence of networks in forest governance on NCP co-production has only been studied implicitly via anthropogenic capitals. For example, Górriz-Mifsud et al. (2016) explored the interlinkages between social capital and governance of natural resources in forests whilst touching upon human, financial, and natural capital. In another study in Catalonia, Górriz-Mifsud et al. (2017) investigated mushroom hunting regulations. They found that social capital, in the form of network interactions, underpinned the establishment of a mushroom hunting permit. Despite these studies, how actors are connected across governance levels via specific anthropogenic capitals in co-producing forest NCP remains uncertain.

To address this research gap, we interviewed local forest actors in three case study sites across Germany and conducted a social network analysis (SNA) to understand how local forest actors perceive the governance of anthropogenic capitals in the co-production of forest NCP. We specifically aimed to (i) unravel which actors were most relevant for the governance of specific anthropogenic capitals in the co-production of forest NCP and (ii) identify patterns of actors and their connections via anthropogenic capitals when governing the co-production of forest NCP.

2 GOVERNANCE LEVELS, POLICIES, AND DATA ANALYSIS

2.1 Case study sites

This research is embedded in the long-term and large-scale research platform *Biodiversity Exploratories*, which investigates how land use affects biodiversity and ecosystem functioning in grasslands and forests (Fischer et al., 2010a). While the ecological impacts of forest management have been studied thoroughly in the *Biodiversity Exploratories* (e.g., Felipe-Lucia et al., 2020, 2018; Getzin et al., 2012; Schall et al., 2018), its social aspects have only recently been considered (Isaac et al., 2024; Kachler et al., 2023a; Peter et al., 2022). This project focuses on three case study sites across Germany, located in the Schorfheide-Chorin (State of

Brandenburg) in the North East, the Hainich-Dün (Free State of Thuringia) in the centre, and the Schwäbische Alb (State of Baden-Württemberg) in the South West (Fischer et al., 2010a) (Fig. 1). Forests in the three case study sites are affected by informal and formal governance arrangements across the local, federal state, German, and European Union (EU) level (Grotz, 2012; Lazdinis et al., 2019).

Schorfheide-Chorin encompasses a UNESCO[3] biosphere reserve, the World Heritage site *Grumsin Forest,* and is characterised by a diverse landscape of forests, lakes, and agricultural fields (Landesamt für Umwelt Brandenburg, 2023; UNESCO, 2023). Hainich-Dün is characterised by a mix of productive forests and agricultural land and contains the Hainich National Park, which hosts another UNESCO World Heritage site (Nationalpark Hainich, 2023; UNESCO, 2023). Schwäbische Alb encompasses a UNESCO biosphere reserve and is characterised by forests and grasslands on a sub-montane and montane plateau (Biosphärengebiet Schwäbische Alb, 2023). Of the *Biodiversity Exploratories*' experimental plots, 13% are unmanaged, 57% are managed broadleaved forests, and 26% are managed conifer forests (Fischer et al., 2010a). Forests in the three sites are governed by formal and informal governance arrangements across the local, federal state, German, and European Union level (Grotz, 2012; Lazdinis et al., 2019).

2.2 Data collection

We conducted 39 semi-structured interviews with local forest actors to understand how they perceive the governance of co-produced forest NCP across multiple levels. The interviews were pre-tested outside the case study sites and adapted accordingly. The final interviews were conducted between May and November 2021 with 33 foresters, one forestry contractor, and two representatives for each biosphere reserve and one representative for Hainich National Park (Fig.1). Most participants were male (n=37) and had an average age of 53.54 years. We selected participants in three ways. First, we asked foresters within the Biodiversity Exploratories' experimental plots to participate. Second, we contacted additional foresters via snowball sampling based on previous interviews. Snowball sampling presents a common technique when collecting data for social networks on NCP (e.g., Aguilar Rodríguez

[3] United Nations Educational, Scientific and Cultural Organization

et al., 2021; Oteros-Rozas et al., 2014) and increases the willingness of potential respondents to participate when referred to by one of their friends or colleagues (Borgatti et al., 2022). Third, we contacted biosphere reserve and national park representatives via their respective administrations.

The interviews started with an exercise in which participants selected the most important five out of 11 NCP and ranked them according to their importance using laminated images and a whiteboard with magnets (Isaac et al., 2022). We solely asked questions for the highest-ranked NCP to avoid respondent fatigue due to lengthy interviews. In this second stage of the interview, we asked questions about the importance of the NCP, the use of different anthropogenic capitals in the management and use of the NCP, and about any other actors and organisations that influence the possibility of producing the NCP in the case study and influence the use of the different anthropogenic capitals. In addition, foresters answered additional questions about timber production and habitat management. For a detailed description of the interview guide and the fieldwork protocol, see Isaac et al. (2022). The interviews were recorded with the respondents' consent and according to the approval of Leuphana University's ethics review committee (EB-Antrag 2021-03_Isaac_ESuDis). Additionally, all participants signed a consent agreement for their data to be used anonymously (Isaac et al., 2022). All interviews were transcribed using the NVIVO software (Alfasoft GmbH, 2023).

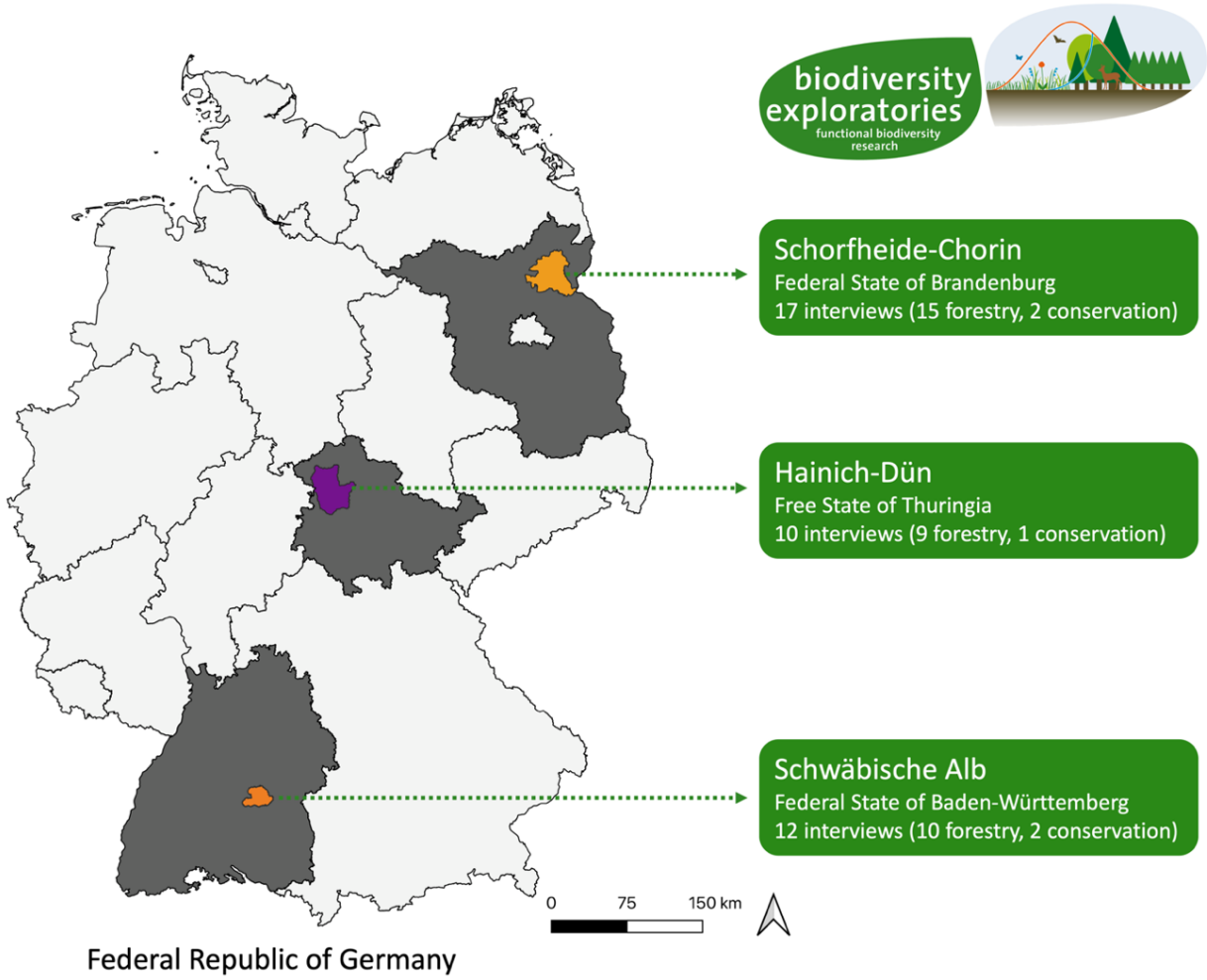

FIGURE 1 Map of the case study sites in Germany indicating the number of interviews per case study site and sector the participants belong to (total number of interviews n=39). Federal states containing case study regions are in dark grey. Sites with biosphere reserves are in orange, while the site with a national park is in purple. This figure is based on data provided by the Biodiversity Exploratories Information System (BExIS) (2022) and Esri Deutschland GmbH (2018).

2.3 Data coding

The interview transcripts were analysed using a predefined coding set encompassing the focal forest NCP (i.e. timber production, climate regulation, habitat creation and maintenance, and non-material NCP), the relationships between actors involved in their co-production, and the anthropogenic capitals by which the actors were connected (Table S2). The coding set captured the participants' perception of who is involved in the co-production of a specific forest NCP and which anthropogenic capitals are used. For example, foresters and the external contractors they commission are connected by manual labour, machinery, and tools used to harvest timber.

To code NCP, we followed the IPBES' generalising perspective on NCP (Díaz et al., 2018). We considered four NCP: (1) timber production, (2) climate regulation that encompassed carbon sequestration and micro-climate regulation, (3) creation and maintenance of habitat (which included habitat maintenance, pollination, and natural pest control, since more diverse habitat likely provides better conditions for species that provide pest control and pollination (Palliwoda et al., 2021)), and (4) the category of non-material NCP that included all physical activities in nature, the observation and enjoyment of plants, animals, and landscape.

To code anthropogenic capitals, we considered different subcategories. Human capital included the subcategories of labour, knowledge, and skills. Social capital had networks and institutions. Physical capital encompassed the sub-categories of tools and machinery, infrastructure, and built capital. Direct payments and subsidies were the sub-categories of financial capital (Palomo et al., 2016). When making a clear distinction was challenging, we combined anthropogenic capital sub-categories. For example, the distinction between the human capitals knowledge and skills seemed to be difficult in a forestry context as they represent inextricably linked aspects of forest management. While the verbatim "*It always depends on the driver who operates the machinery. It all depends on him. The driver's experience and motivation if he identifies with what he does. Well, he does need a bit of experience. I hired [Anonymous] in '91. He's been here 30 years, and he is a trained forestry worker. So, he knows what trees are, the tree species, how they grow, and their needs.* (Forester JK74 Schorfheide-Chorin)" shows a clear distinction between skills ("the driver's experience") and knowledge ("knows what trees are…"); the verbatim "*I was at a one-day-long training two weeks ago. We have forest education centres around here that provide these. They have developed something new in [name of place], on how you combine manual harvesting with a chainsaw with the harvester to process long timber.* (Forester JK129 Schwäbische Alb)" illustrates the intertwined connection between skills and knowledge and the difficulty of explicitly coding each. In the second verbatim, we combined both subcategories of human capital.

Finally, we regrouped the 102 individual actors identified by the participants into seven actor groups: Biodiversity Exploratories (i.e., project representatives and the local management teams in each case study site), foresters, forest industry (i.e., contractors, sawmills), forest owners, government (i.e., local, state, and German government, EU),

protected areas (i.e., biosphere reserve, national park), and societal actors (i.e., NGOs, associations).

2.4 Social Network Analysis

Social networks are formed by actors via one or multiple interactions (Marin and Wellman, 2011). Actors within social networks are referred to as nodes, and their connections are known as ties. Attributes are the characteristics describing nodes or ties, e.g., for nodes, an actor's profession, age, or gender (Borgatti et al., 2022); or for ties, the quality, speed, or some other property beyond the interaction that creates the tie. Ties can be directed, indicating, for example, the flow of information from one node to another but not vice-versa, or undirected, as in our study (Marin and Wellman, 2011). In this study, we treat the actor's group membership as their primary attribute of interest.

In SNA, centrality measures provide insights into how individual nodes might affect flows through the broader network concerning other neighbouring nodes (Hannemann and Riddle, 2011). In this paper, we focus on three measures of centrality. First, degree centrality measures "the number of ties of a given type that a node has" (Borgatti et al., 2022, p. 171). It is the simplest centrality measure and describes only local connectivity. Second, betweenness centrality measures how often a node connects two otherwise detached nodes (Borgatti et al., 2022). This is measured as the number of times a node falls on the shortest path between each pair of nodes in the network. The higher a node's betweenness centrality, the more significant its role in connecting other nodes and potentially the higher its level of control over network dynamics (Hannemann and Riddle, 2011). Thus, nodes with a high betweenness centrality act as gatekeepers within the network (Borgatti et al., 2022). Third, eigenvector centrality measures how often a node is connected to other well-connected nodes and can thus be interpreted "as a measure of popularity in the sense that a node with high eigenvector is connected to nodes that are themselves well connected" (Borgatti et al., 2022, p. 173). These centrality measures typically exhibit considerable redundancy; we measured all three because each illuminates a slightly different aspect of a node's contribution to network structure and potential function.

Based on the interview data, we generated and visualised four individual NCP networks (timber production; climate regulation; habitat creation and maintenance; non-

material NCP) and a combined network based on these using NodeXL and Gephi (Fig. 2-6) (Bastian et al., 2009; Smith et al., 2010). The nodes within each network represent the actors identified by the participants. The ties between the nodes represent the anthropogenic capitals used by the actors to co-produce forest NCP (see legend of Fig. 2-6). Further, after calculating degree centrality, betweenness centrality, and eigenvector centrality for each node in each network, we used a non-parametric Kruskal-Wallis test to identify whether differences for the centrality metrics existed among actor groups. First, we tested for differences between the actor groups involved in the co-production of each focal NCP and the combined NCP network. Second, we tested whether actor groups differed regarding their connections when using specific anthropogenic capital in the co-production of each NCP. When Kruskal-Wallis reported significant differences, we used Dunn's pairwise comparison tests in both cases to evaluate differences between actor groups. Significant differences between actor groups showed that actors are connected via anthropogenic capitals in three patterns in which forest NCP are co-produced. All statistical analyses were performed in XLSTAT 2020.3.1, a plugin for Microsoft Excel (Addinsoft, 2023).

2.5 Methodological limitations

Our analysis is subject to several limitations. First, similar to other SNA studies (e.g. Knoot and Rickenbach 2014), we used interviews with forest actors as the basis for our analysis. However, we could not reach a high network coverage due to COVID-19 travel restrictions and the reluctance of some foresters to be interviewed due to their employment as public servants. Thus, we could not commit to a whole network approach but rather followed an extended egocentric network approach by including those nodes connecting to direct contacts of an individual actor, e.g., “friends of friends” (Marin and Wellman, 2011, p. 20). Second, our analysis mainly relied on snowball sampling as respondents referred us to their colleagues which may have lead to a bias as this method favours highly connected actors (van der Hulst, 2011). However, combining sampling techniques, as done here by approaching respondents directly, is beneficial when obtaining network data compared to following a random sampling approach (Maciejewski and Baggio, 2021). Third, caution must be taken when generalising our findings since our analysis was based on the perceptions of local forest actors in three German case study sites. Forests in these case study sites are managed under

the so-called “German model” favouring integrative and multifunctional management (Borrass et al., 2017) and are strongly regulated by policy documents across governance levels (Isaac et al., 2024; Sotirov and Storch, 2018). Thus, forest actors are limited in making decisions freely and may choose specific anthropogenic capitals due to management regulations.

3 RESULTS

3.1 Governance networks affecting capitals in the co-production of forest NCP

Our SNA identified four separate forest NCP networks and a global network, including all NCP. Nodes representing actors indicated the actor’s group based on the node colour and the governance level at which the actor operates based on the node shape. Tie styles represent the anthropogenic capital by which actors are connected (Fig. 2-6).

For the combined network, we found that the Biosphere Reserve administration in Schorfheide-Chorin (SCH Biosphere Reserve) had the highest degree centrality (Fig. 2). Moreover, we found that the EU, referred to by actors mainly due to policies, had the highest betweenness centrality in the combined network since it facilitated most connections of otherwise unconnected actors and thus exerts most control over the network. Schwäbische-Alb’s local government (ALB Government) had the highest eigenvector centrality, thus being most connected to other well-connected nodes (Fig. 2). Here, government refers to several municipalities and district authorities. Despite not being central to the network, the Biodiversity Exploratories connected actors across the case study sites via human capital (orange diamond in Fig. 2). In addition, we found highly significant differences between actor groups in the combined network for degree (χ^2=19.696, d.f.= 6, p<0.003) and betweenness (χ^2=23.392, d.f.= 6, p<0.001). Dunn's multiple comparison test ($p < 0.01$) indicated that forest owners had the highest degree centrality while betweenness centrality was highest for the Biodiversity Exploratories and forest owners (Table S3).

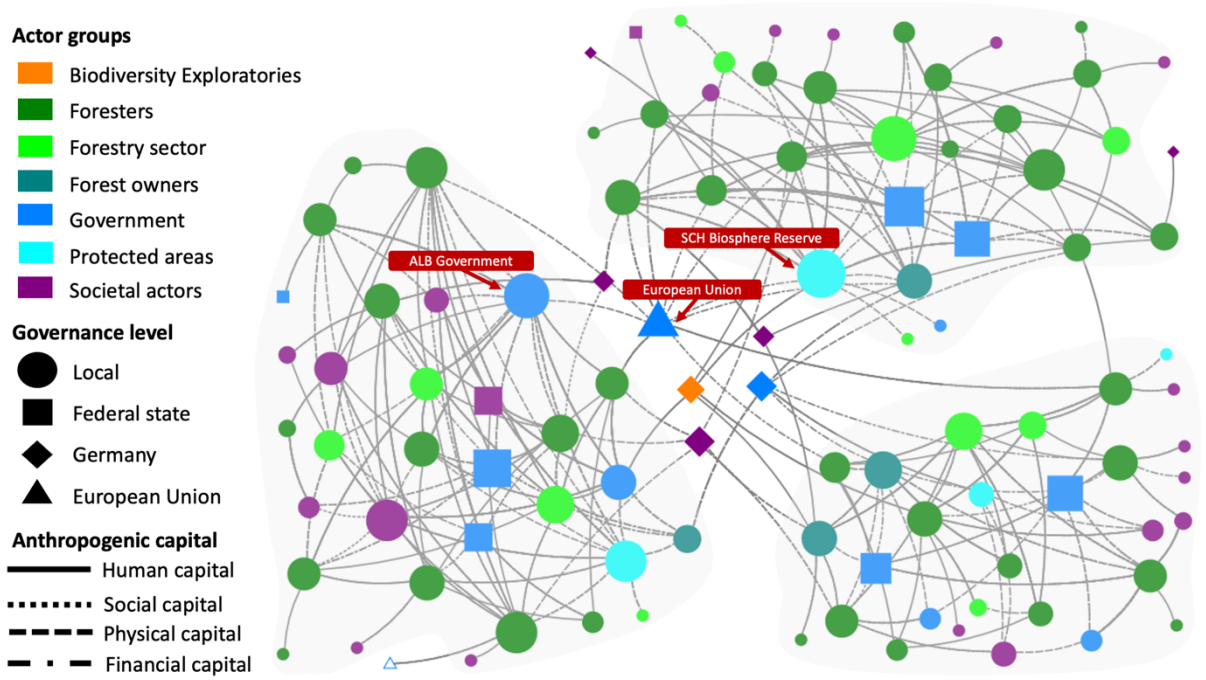

FIGURE 2 The combined network displaying the perceived connections between actors across multiple governance levels involved in the co-production of forest NCP. Highlighting the three case study sites. Node size represents the actor's degree centrality, node colours represent the actor group, node shapes represent the governance level at which this actor operates (local, federal state, German national, or EU level), and ties represent the anthropogenic capitals according to the legend. Tie strength is not considered. Grey underlay indicates actors in the same case study site and federal state.

3.2 Timber production

The network for the co-production of timber was dominated by foresters, forest owners, and actors in the forestry sector (Fig. 3). We found that forestry contractors in Schorfheide-Chorin (SCH forestry contractors), who are commissioned to harvest timber, had the highest degree centrality, thus being connected to the highest number of actors. Contractors contribute to the timber harvest through manual labour as well as their skills and knowledge when operating machinery, such as harvesters, forwarders, or trucks. Forest certification (GER forest certification), referring to forest certification by the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification Schemes (PEFC), had the highest betweenness centrality, hence exerting high control over the network by providing social capital in the form of rules for forest management according to their standards. Forestry contractors in Schwäbische Alb (ALB Forestry contractors) scored highest for highest eigenvector centrality by being most connected to other well-connected nodes (Fig. 3). We did not find significant differences between centrality metrics among the actor groups involved in the co-production of timber. However, we found differences in degree (χ^2=7.728,

d.f.= 3, p<0.052) and betweenness centrality (χ^2=7.068, d.f.= 3, p<0.070) between actor groups when specifically considering their influence in the use of financial capital (Table 1). Forest owners as a group scored highest for degree and betweenness centrality (based on Dunn's multiple comparison test (p < 0.01), Table S4). Here, the SNA and the conducted tests revealed a pattern showing the importance of forest owners for timber production by being connected to other actors via financial capital, referred to as *Pattern 1 governance of timber production via financial flows*. This pattern illustrates how financial capital is used by forest owners to govern timber production since they not only generate revenue for profit but also use this capital to pay contractors for their work. Forest owners receive financial capital as governmental funding for afforestation or reforestation measures and to leave deadwood.

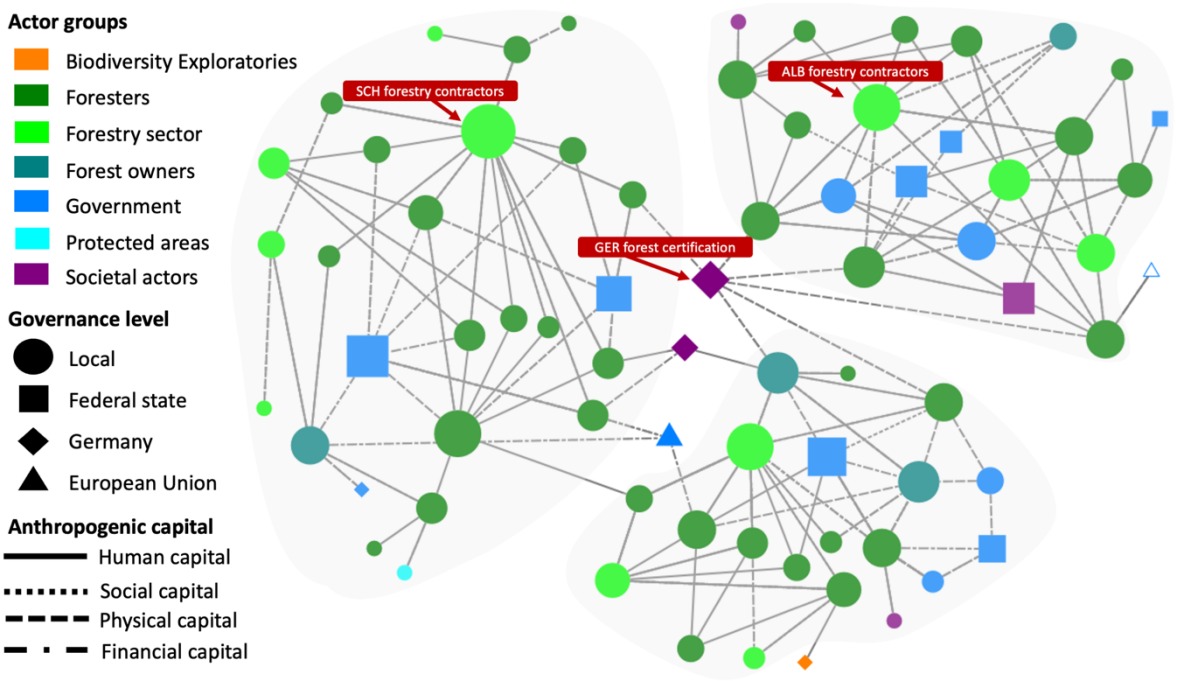

FIGURE 3 The network for timber production displays the perceived connections between actors across multiple governance levels involved in the co-production **timber**. Node size represents the actor's degree centrality, node colours represent the actor group, node shapes represent the governance level at which this actor operates (local, federal state, German national, or EU level), and ties represent the anthropogenic capitals according to the legend. Tie strength is not considered. Grey underlay indicates actors in the same case study site and federal state.

3.3 Climate regulation

In contrast to the network for timber production, we found fewer connections between actors and a less dense network for climate regulation (Fig. 4). The Biosphere Reserve administration in Schorfheide-Chorin (SCH Biosphere Reserve) had a central position in this

network. We found that it not only had the most connections (highest degree centrality) but scored highest for betweenness centrality and eigenvector centrality. We found differences for degree centrality among actor groups influencing the use of anthropogenic capitals underpinning regulation of climate (χ^2=11.20, d.f.= 6, p<0.082). The protected areas actor group had the highest degree centrality (but no significant differences based on Dunn's multiple comparison test (p < 0.01), Table S3). We found differences for eigenvector centrality among actor groups when specifically considering their influence in the use of human capital to regulate climate (χ^2=7.700, d.f.= 3, p<0.053; Table 1). The Biodiversity Exploratories disseminated scientific knowledge while forest industry actors, especially contractors, used manual labour to co-produce climate regulation, e.g., via reforestation practices. Since these two actor groups had the highest eigenvector centrality (but no significant differences based on Dunn's multiple comparison test (p < 0.01), Table S5) and are thus highly connected to other well-connected nodes in the climate regulation network, their influence can be executed via expert knowledge and the use of manual labour is referred to as *Pattern 2 governing knowledge and labour for climate regulation*.

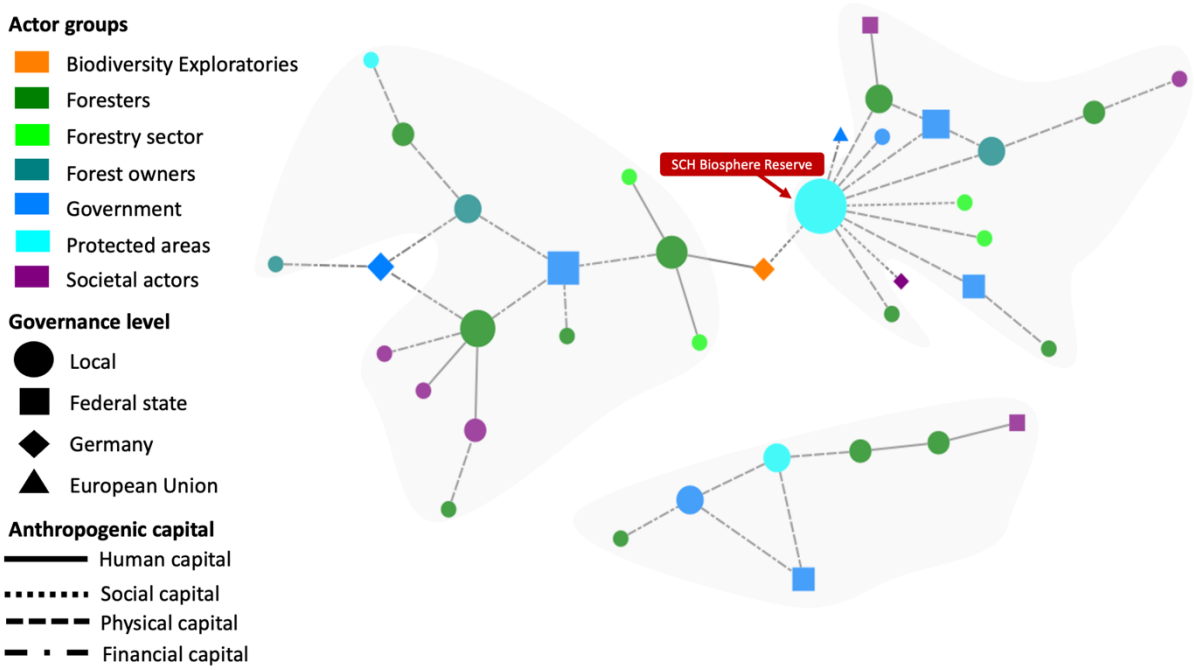

FIGURE 4 The network for the regulation of **climate** displays the perceived connections between actors across multiple governance levels contributing to climate regulation. Node size represents the actor's degree centrality, node colours represent the actor group, node shapes represent the governance level at which this actor operates (local, federal state, German national, or EU level), and ties represent the anthropogenic capitals according to the legend. Tie strength is not considered. Grey underlay indicates actors in the same case study site and federal state.

3.4 Habitat creation and maintenance

The network that represents the actors involved in the use of anthropogenic capitals underpinning the co-production of habitat creation and maintenance included more actors (Fig. 5) than the network of climate regulation. The analysis showed that this network was the only one in which five actors scored highest for degree centrality: an ornithologist (ALB Expert) and a forester (ALB Forester9) in the Schwäbische Alb case study, a forester (SCH Forester5) and the Biosphere Reserve administration (SCH Biosphere Reserve) in Schorfheide-Chorin, and the EU, which also scored highest for betweenness centrality. A local non-governmental organisation (NGO) in Schwäbische Alb scored highest for eigenvector centrality (ALB NGO). Moreover, we found significant differences for degree centrality (χ^2=13.003, d.f.= 6, p<0.043) and betweenness centrality (χ^2=14.502, d.f.= 6, p<0.025) among actor groups influencing the use of capitals underpinning the creation and maintenance of habitat. The actor group of protected areas was the most relevant in both (Dunn's multiple comparison test (p < 0.01); Table S3). Similarly, we found differences for degree centrality (χ^2=11.475, d.f.= 5, p<0.043) and betweenness centrality (χ^2=10.374, d.f.= 5, p<0.065) among actor groups when specifically considering their influence in the use of social capital to create and maintain habitat (Table 1). The protected areas group was the actor group with the highest degree centrality and betweenness centrality. Still, based on Dunn's multiple comparison test (p < 0.01), Table S6), there were no significant differences between groups. Thus, protected areas were found to be important to many other actors by having most individual connections and act as a gatekeeper for governing the creation and maintenance of habitat by enforcing formal conservation rules (social capital). This dual role of protected areas is described as *Pattern 3 governance for habitat management*.

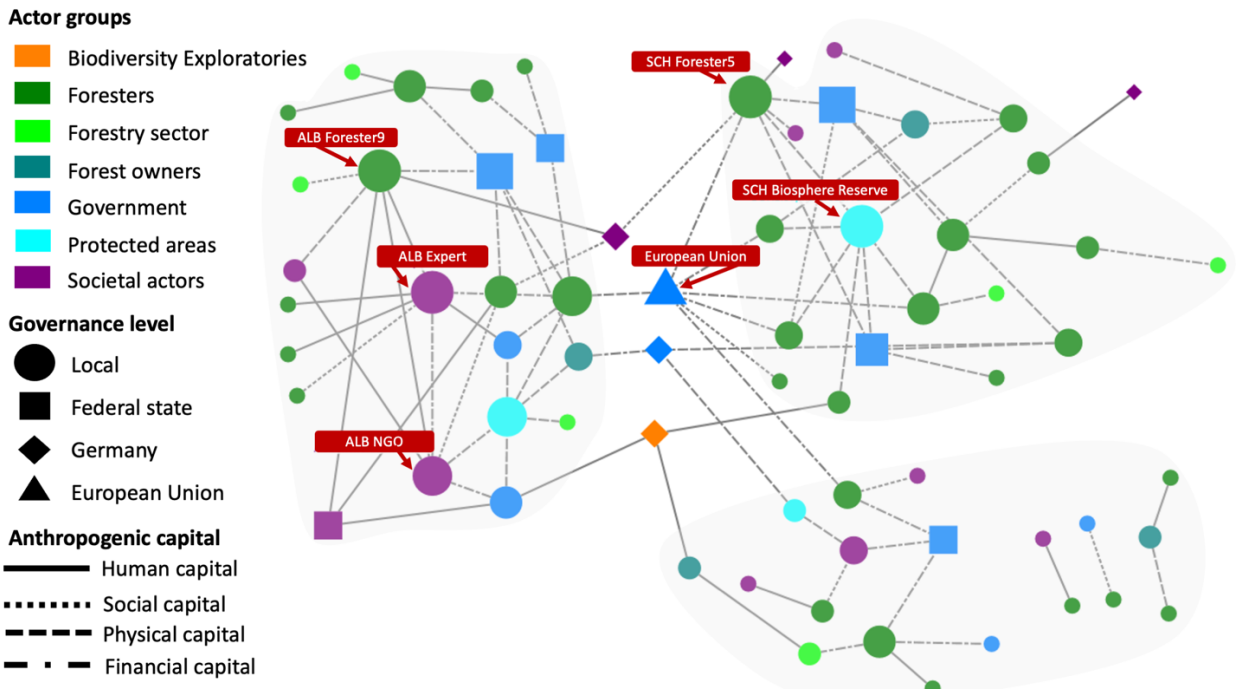

FIGURE 5 The network for the **creation and maintenance of habitat** displays the perceived connections between actors across multiple governance levels contributing to this NCP. Node size represents the actor's degree centrality based on degree, node colours represent the actor group, node shapes represent the governance level at which this actor operates (local, federal state, German national, or EU level), and ties represent the anthropogenic capitals according to the legend. Tie strength is not considered. Grey underlay indicates actors in the same case study site and federal state.

3.5 Non-material NCP

Our network analysis showed that the network for non-material NCP was more fragmented, and actors were more loosely connected than in the other NCP networks. Most interactions between actors were found in the Schwäbische Alb case study (Fig. 6). A local NGO in Schwäbische Alb (ALB NGO) scored highest for degree centrality, betweenness centrality, and eigenvector centrality. The NGO was described to manage local infrastructure for recreational activities, such as hiking trails, and was connected to other actors by all four capital categories. In contrast to the other NCP networks, we neither found significant differences between actor groups involved in the co-production of non-material NCP (Table S4) nor between actor groups in the use of specific anthropogenic capitals (Table 1, Table S7).

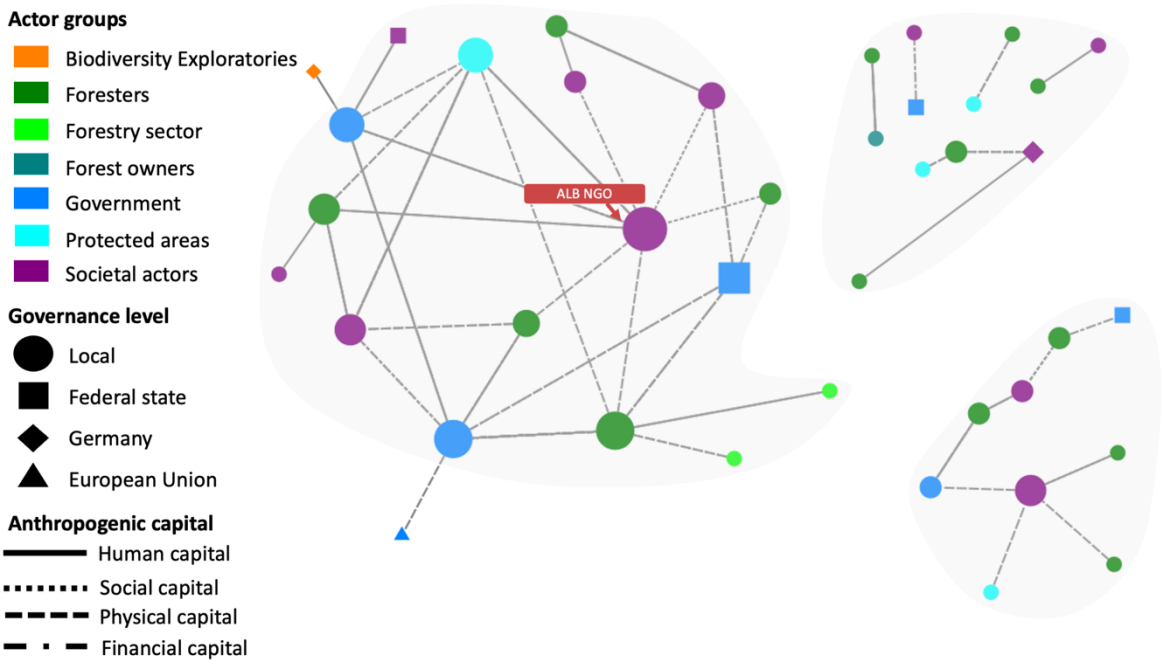

FIGURE 6 The network for **non-material NCP** displays the perceived connections between actors across multiple governance levels contributing to this NCP. Node size represents the actor's degree centrality, node colours represent the actor group, node shapes represent the governance level at which this actor operates (local, federal state, German national, or EU level), and ties represent the anthropogenic capitals according to the legend. Tie strength is not considered. Grey underlay indicates actors in the same case study site and federal state.

TABLE 1 P-values resulted from the Kruskal-Wallis test for degree centrality, betweenness centrality, and eigenvector centrality showing differences between actor groups regarding their influence in the use of each anthropogenic capitals underpinning the co-production of timber production, climate regulation, habitat creation and maintenance and non-material NCP. Significant p-values are presented in bold font.

		Nature's contributions to people (NCP)			
Anthropogenic capital category	**Network centrality metric**	**Timber production**	**Climate regulation**	**Habitat creation & maintenance**	**Non-material NCP**
Human capital	Degree	0.115	0.169	0.384	0.399
	Betweenness	0.183	0.169	0.325	0.374
	Eigenvector	0.207	**0.053**	0.243	0.536
Social capital	Degree	0.253	0.394	**0.043**	0.799
	Betweenness	0.295	0.461	**0.065**	0.699
	Eigenvector	0.369	0.887	0.320	0.677
Physical capital	Degree	0.265	-	0.883	0.299
	Betweenness	0.276	-	0.883	0.299
	Eigenvector	0.725	-	0.630	0.437
Financial capital	Degree	**0.052**	0.260	0.341	0.533
	Betweenness	**0.070**	0.322	0.640	0.262
	Eigenvector	0.774	0.850	0.884	0.979

4 DISCUSSION

We employed social network analysis (SNA) based on 39 interviews to investigate how actors influence the co-production of multiple nature's contributions to people in forests in three German sites. Similar to Borg et al. (2015), we interviewed forestry and conservation actors. Our analyses uncovered different actor constellations affecting the co-production of each focal NCP, i.e., timber production, climate regulation, creation and maintenance of habitat, and non-material NCP. The SNA showed three patterns of actors being connected via anthropogenic capitals and influencing how co-produced forest NCP are governed: (1) *governance of timber via financial flows*, (2) *governing knowledge and labour for climate regulation*, and (3) *governance for habitat management*. In the following, we discuss the relevance of our findings considering the debate on NCP co-production and the governance of forests.

4.1 Actor contributions to co-producing forest NCP

The combined network of actor-to-actor relationships for four NCP, including material, regulating, and non-material NCP (Fig. 2), reflects the diverging and sometimes conflicting demands that forest management in Germany seeks to account for and integrate (Borrass et al., 2017). Three main messages can be derived from the analysis of this network. First, regional context is essential when discussing decision-making processes in forest management (Knoot and Rickenbach, 2014). Biosphere reserves, for example, provide a setting in which the co-production of various NCP can be achieved (Palliwoda et al., 2021) and were established to enhance cooperation among actors (Stoll-Kleemann and O'Riordan, 2018). Thus, biosphere reserves can be described as a "designated coordinator" facilitating collaboration within the network (Bodin, 2017, p. 6). Our findings illustrate the participatory and collaborative nature of biosphere reserves in the case of governing the co-production of forest NCP (Schultz et al., 2011) since both biosphere reserve administrations Schorfheide-Chorin (degree centrality) and Schwäbische Alb (eigenvector centrality) ranked high for centrality metrics. Second and similar to other social-ecological interactions, the co-production of forest NCP is governed by actor relationships across levels that facilitate the coordination of actors at one level, in this case study (Bodin, 2017). The EU is an example of

coordinating other actors by influencing forest management indirectly via various conservation policies, for example, via the Habitats Directive (92/43/EEC) that drives habitat creation and maintenance in Natura 2000 areas (Elomina and Pülzl, 2021). Third, our findings for actor groups indicate that relationships between forest owners strongly drive forest management decisions that influence the use of specific anthropogenic capitals. These results align with Stoettner and Ní Dhubháin (2019) and Westin et al. (2023), who found that forest owners' values and degree of engagement within social networks influence their management strategies. Remarkably, and complementing the vital role of forest owners, we found the Biodiversity Exploratories to be the group with the highest betweenness centrality. This indicates its relevant role as a knowledge broker across the three case study sites as the Biodiversity Exploratories can facilitate collective learning through collaboration with other actors (Bodin, 2017).

4.2 Timber production

Timber production in the three case study sites appears to be strongly influenced by forestry contractors in Schorfheide-Chorin (highest degree centrality) and Schwäbische-Alb (highest eigenvector centrality) (Fig. 3). Here, our findings align with Johansson et al. (2021) who describe contractor's competence and resources, a human and a physical capital, as critical factors influencing their performance during timber harvest. Timber production and forests are also affected by certification schemes (Galati et al., 2017; Rametsteiner and Simula, 2003). Thus, the central role of forest certification bodies, such as PEFC and FSC, is unsurprising since 75 to 83% of forests in Germany were certified in 2019 (Umweltbundesamt, 2020). Although forest owners' and forest industry actors' motivations differ and include external and internal motives, their main aim when adopting certification schemes lies in improved marketing opportunities and company appearance regarding sustainability (Zubizarreta et al., 2021). Similar observations have been made within the three case studies as forest owners and other forestry actors were found to prioritise material NCP, such as timber production, and to perceive biodiversity loss as a significant risk to the economy (Peter et al., 2022). This is in line with *pattern 1 governance of timber via financial flows*, which indicates that forest owners not only favour timber to generate profit by selling it to markets (Knoot and Rickenbach, 2014)

but also use financial capital to govern the use of other anthropogenic capitals that contribute to the co-production of timber.

4.3 Climate regulation

Climate regulation within the three case study sites depends on the biosphere reserve's administration mediating role and the strict protection of forests in the biosphere reserve core zones (Stoll-Kleemann and O'Riordan, 2018). Untouched forest, as in biosphere reserve core zones or national parks, was found to have the highest carbon stocks in living biomass (Duncker et al., 2012). In contrast to strict protection for carbon sequestration, the second pattern *governing knowledge and labour for climate regulation* stresses that, for one, the Biodiversity Exploratories are regarded as an expert organisation that contributes to improving climate regulation by disseminating knowledge. This finding aligns with the *Biodiversity Exploratories* project's aim to provide data and knowledge gathered in their research to inform forest management in the three case studies (Fischer et al., 2010b). Second, forest industry actors, particularly contractors, appear to contribute to climate regulation through afforestation and reforestation, which have been described as increasing carbon stocks in forests (Jandl et al., 2007). For example, planting seedlings in afforestation or reforestation settings is labour-intensive. It requires suitable machinery, such as mechanised transplanters or tree planters, and specific skills and knowledge to operate these machines. Thus, efforts to increase carbon stocks depend on forest management strategies and the contractors' skills and knowledge.

4.4 Habitat creation and maintenance

Habitat creation and maintenance in the three case study sites appear to depend on the collaboration of various actors. Collaborative governance aims to balance diverging interests but does not necessarily entail solving social-ecological problems (Bodin, 2017), for example, the sustainable co-production of NCP. Collaboration in nature conservation contexts is often based on trust and exchanging information between like-minded actors (Borg et al., 2015). Biosphere reserves are protected areas that foster local actors' participation and collaboration to reach conservation goals (Batisse, 1982). Thus, collaborative and

participatory approaches to preserving habitats in biosphere reserves were found to be more successful than strict top-down conservation measures (Stoll-Kleemann et al., 2010). For example, in our network collaboration between local actors and an NGO in the Biosphere Schwäbische Alb illustrates how collaboration for maintenance can contribute to the conservation of habitats (Geschäftsstelle Biosphärengebiet Schwäbische Alb, 2019). Similarly but in a very different context, local NGOs in Indonesia's Borneo forest have been described to foster participation in conservation through community-based forest management (Friedman et al., 2020). Despite collaborative efforts on the case study level, our analysis indicated that top-down governance via the EU's Natura 2000 network contributes to creating and maintaining habitat by improving the collaboration of local actors via increasing "vertical fit" as they need to manage the designated sites (Bodin, 2017, pp. 4–5). Pattern 3 *governance for habitat management* through social capital illustrates how protected areas support multiple NCP by enforcing top-down regulations to maintain habitats (Metzger et al., 2020). Additionally, they act as mediators between various governmental and civil society actors and thus bridge interests regarding the provision of forest NCP across sectors and governance levels (Keskitalo et al., 2014; Yamaki, 2016). Protected areas can thus be described as "designated coordinators" of the creation and maintenance of habitat network (Bodin, 2017, p. 6).

4.5 Non-material NCP

Previous research has demonstrated how non-material NCP are provided and co-produced in protected areas and biosphere reserves in particular (Eastwood et al., 2016; Palliwoda et al., 2021). For one, good conservation status increases the potential for non-material NCP (Maes et al., 2012). Second, accessibility has been described as important for visitors to protected areas (Crouzat et al., 2022). The existence of good infrastructure makes easy access to natural areas possible and thus facilitates obtaining non-material NCP (Schägner et al., 2016). Within our case studies, the Biosphere Reserve Schwäbische Alb has been described to be valued for its recreational opportunities by local and non-local visitors (Müller et al., 2019). Visitors were found to realise the potential supply of non-material NCP by engaging with nature as a space of cultural heritage or through recreational activities in nature, such as hiking or cycling (Bieling, 2014). Thus, non-material NCP not only depend on their provision but their realisation by their beneficiaries (Bruley et al., 2021). Our findings support the notion that

infrastructure is essential to co-producing non-material NCP but highlights that collaboration is useful when managing this infrastructure. This is due to observing that the management of managing hiking trails by a local NGO is done in close collaboration with the Biosphere Reserve administration, regional tourism organisations, as well as local conservation and forest authorities (Geschäftsstelle Biosphärengebiet Schwäbische Alb, 2019). In contrast to the Biosphere Reserve Schwäbische Alb, our findings for the other two case study sites only partially provided evidence and actors were fragmented regarding the co-production of non-material NCP. For one, this may have been due to our focus on foresters and conservation managers and thus excluding representatives from tourism organisations. Second, the low availability of respondents in the other areas may have led to finding fewer references to non-material NCP. Third, the Biosphere Reserve Schwäbische Alb is known for its cultural heritage and located in close proximity to several densely populated areas and recreational focus by visitors (Kachler et al., under review).

4.6 Outlook for research and decision-making

The three governance patterns involved in the co-production of forest NCP highlight that further underlying causes need to be understood to achieve sustainable forms of NCP co-production.

First, material NCP, in this case timber production, are governed by few actors and depend on the flow of financial capital to be co-produced. Thus, despite increased societal demands and management efforts for the provision of non-timber-based NCP, forest owners are still strongly focused on the production of timber as a source of income (Borrass et al., 2017; Peter et al., 2022). Hence, future research needs to further investigate and provide evidence to decision-makers and forest managers on how other non-monetizable NCP, including non-wood forest products, regulating, and non-material NCP, can be promoted by introducing new forms of financial income and thus reducing the dependence on timber sales (Hernández-Morcillo et al., 2022).

Second, aside from re-forestation through tree planting, our study shows that the sharing of knowledge by experts is essential for supporting climate regulation, and likely other regulating NCP as well. Collaborative learning has been described to be beneficial when addressing complex environmental problems, such as climate change (Bodin, 2017). While

researchers are often criticised for falling short of communicating scientific findings and making them applicable to practice, participatory communication formats are positively linked to how researchers are perceived by the greater public (Suldovsky et al., 2017). Therefore, researchers should communicate their findings and engage with stakeholders to generate knowledge relevant for the sustainable co-production of regulating NCP (Chambers et al., 2021).

Third, our study showed that the creation and maintenance of habitat depend not only on the collaboration of diverse actors via various anthropogenic capitals but also on the coordination of protected areas. Management coordination is mainly undertaken if protected areas lack formal power to enforce habitat conservation measures (Stoll-Kleemann et al., 2010). Nonetheless, power is crucial for promoting some NCP over others (Juerges et al., 2020). For example, strong high timber prices incentivise increasing timber harvests instead of voluntarily protecting habitat, which does not generate any direct income. This prioritisation will lead to favouring heavy machinery for harvesting, which will negatively affect the properties of forest soils (Ampoorter et al., 2007). Thus, future research and decision-makers need to address how formal and informal power asymmetries influence the use of anthropogenic capitals and favour or neglect specific NCP. For example, community-based management has been described as beneficial to forest governance by empowering otherwise marginalised actors and promoting synergies between NCP (Fischer et al., 2023). Still, it may come at a loss of rights for some actors (Hajjar et al., 2020).

5 CONCLUSION

This paper aimed to understand which actors are most relevant in the management of different anthropogenic capitals involved in the co-production of forest NCP and identify governance patterns of these NCP. To fulfil this aim, we conducted interviews with forest actors across three case study sites in Germany and performed a social network analysis. Our findings highlight that the co-production of material NCP is governed by a few actors and facilitated by financial capital flows. In contrast, the co-production of regulating NCP depends on collaboration between a broad range of actors and the coordination by protected areas. Furthermore, albeit not statistically significant, we found that the governance of NCP co-production was related to collaboration between actors in managing infrastructure that

facilitates access to natural areas. These findings contribute to a better understanding of the underlying actor relationships that favour the use of certain capital in the co-production of NCP and thereby shape whether co-production processes can be sustainable.

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SUPPLEMENTARY MATERIAL

S1 Table. Defining anthropogenic capitals that underpin nature's contributions to people co-production.

S2 Table. Coding set for the interview transcripts to elicit actor to actor relationships in the co-production of nature's contributions to people in forests.

S3 Table. Mean values and Chi-squares for degree, betweenness, and eigenvector of actor groups contributing to the combined NCP network and each focal NCP network (timber production, climate regulation, creation and maintenance of habitat, non-material NCP).

S4 Table. Mean values and Chi-squares for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the co-production timber.

S5 Table. Mean values and Chi-squares for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the regulation of climate.

S6 Table. Mean values and Chi-squares for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the creation and maintenance of habitat. Bold values represent the actor group with the highest mean value for the respective centrality metric.

S7 Table. Mean values and Chi-squares for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the co-production of non-material NCP. Bold values represent the actor group with the highest mean value for the respective centrality metric.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Chapter V

Governing the co-production of nature's contributions to people:

the road ahead

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CHAPTER ONE

Governing the co-production of nature's contributions to people: the road ahead

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Contents

Abstract

Nature's contributions to people (NCP) support human well-being in multiple ways and are provided through an interplay of natural and anthropogenic capitals. This process is also known as NCP co-production. NCP and the capitals that co-produce them are subject to formal and informal institutions in governance settings across spatial, temporal, and administrative scales. Recent research has shown how scientific literature has studied the governance of anthropogenic capitals in the co-production of NCP. Here we build on this research by exploring challenges and highlighting research gaps and challenges. These include conceptual gaps, such as defining what makes NCP co-production sustainable and differentiating social capital from governance. Second, gaps regarding research practices such as increasing inclusivity of stakeholders. Third, thematic gaps include the understanding of power in polycentric governance of co-produced NCP and the identification of leverage points in a transformation towards sustainable forms of NCP co-production. By identifying these gaps, we explore how future research could deepen the understanding of the interplay between natural and anthropogenic capitals in NCP co-production and thus contribute to more sustainable management practices.

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1. Status

Nature's contributions to people (NCP), including ecosystem services, support human well-being in multiple ways (Díaz et al., 2015). NCP can either be material (e.g., food, building materials, or energy), regulating (e.g., regulation of climate or freshwater), or non-material (e.g., psychological or physical experiences) (Díaz et al., 2018). While NCP were long regarded as "free gifts" provided by nature (Spangenberg et al., 2014, p. 41), they are often co-produced by humans (Palomo et al., 2016). Lavorel et al. (2020) define the co-production process as "the emergence of benefits from nature to people through multiple, long-term and dynamic socio-ecological interactions and the associated interplay of natural and human-derived capitals" (p. 3). Natural capital refers to the ways nature supports NCP, while human-derived capitals, also referred to as anthropogenic capitals, are specified into four categories: human (e.g., skills, knowledge, motivation, labour), social (e.g., rules, norms, networks), physical (e.g., infrastructure, machinery), and financial capital (e.g., savings, subsidies, credits) (Isaac et al., 2022; Palomo et al., 2016). Although NCP co-production has been studied across ecosystems, for example, in mountains (e.g., Lavorel et al., 2020), oceans (e.g., Outeiro et al., 2017), forests (Fischer and Eastwood, 2016), and grasslands (e.g., Bruley et al., 2021), only a few studies refer to the interplay of natural and anthropogenic capitals explicitly (Kachler et al., 2023).

Both NCP and the capitals involved in their co-production are subject to various governance processes. Governance of NCP reaches beyond the institutional realm. It refers to "the processes by which a range of actors (e.g. government, resource users, environmental groups and private entities) make decisions that influence the use of ecosystem (s)" and their contributions to human well-being (Metzger et al., 2020, p. 2). Besides, governance processes can span across levels, from local to global (Hooghe and Marks, 2010), and may be organised in different intersecting modes of governance, for example, in a hierarchical (top-down), collaborative (bottom-up), or science-based manner, or via financial nudging (Primmer et al., 2015) (Fig. 1). While governance of NCP has received increasing attention over the past decade (Winkler et al., 2021), research has so far largely neglected how governance affects the use of anthropogenic capitals in NCP co-production processes (Isaac et al., 2022).

According to the scientific literature, anthropogenic capitals in NCP co-production are governed across levels but predominantly at the local level (Isaac et al., 2022). Governance is mainly studied with the co-production of

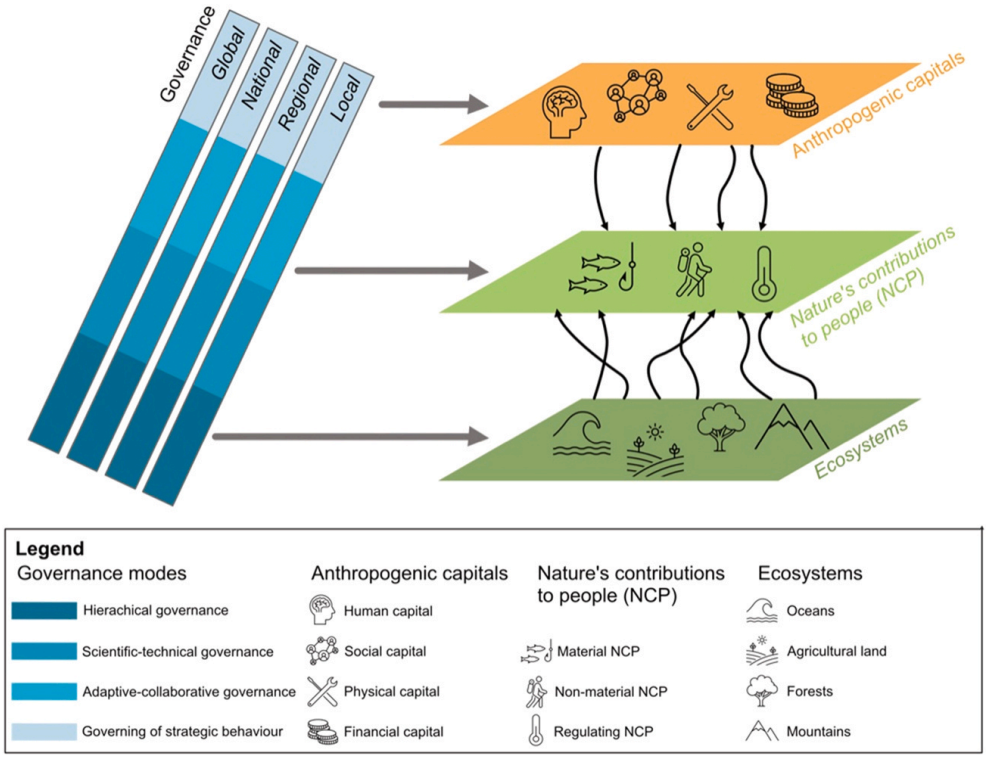

Fig. 1 Different modes of governance (Primmer et al., 2015) at various governance levels ranging from local to global influence the interplay of anthropogenic capitals with ecosystems that underpin the provision of nature's contributions to people (NCP) (Palomo et al., 2016). Governance modes, anthropogenic capitals, NCP, and ecosystems portrayed in this figure are exemplary.

material and regulating NCP and is executed by combining various modes of governance, with strong influence of hierarchical top-down and collaborative bottom-up approaches (Isaac et al., 2022). Depending on the context, governance modes occur in combinations that may complement or potentially also oppose each other in supporting NCP co-production (Isaac et al., 2022). For example, newly formed collaborations between various local actors operate in a formally protected biosphere reserve in Sierra Madre de Chiapas, Mexico, which provides opportunities for silvopastoral management in forests and on agricultural land (Jackson et al., 2012). Moreover, Isaac et al. (2022) found that governance of anthropogenic capitals in NCP co-production is arranged around three clusters. First, governance supports the use of human and financial capital in co-producing material NCP by providing governmental funding. Second, top-down governance enforces social capital in the shape of formal rules and institutions that support the provision of non-material NCP. Third, collaborative and science-based

governance influences how physical capital is used to support regulating NCP (Isaac et al., 2022). These clusters portray the different layers of complexity inherent to governing anthropogenic capitals in NCP co-production (Fig. 1).

2. Current and future challenges

Despite an increasing number of studies on NCP co-production (Kachler et al., 2023), several challenges for future research remain in unravelling the various layers of complexity associated to the governance of anthropogenic capitals in NCP co-production. Below we list the most relevant ones, from simpler to more complex challenges.

- *Expanding the spatio-temporal scope of case study sites to inform territorial planning*. So far, most studies on the governance of NCP co-production have been conducted in European and African countries (Isaac et al., 2022). Thus, future research should focus its efforts on countries on other continents, which have received little attention so far, e.g. Asia and Oceania, or are under strong pressures from natural capital extraction and habitat destruction (FAO, 2022). Besides, further research on the interactions between anthropogenic capitals and NCP across scales and time is needed (Kachler et al., 2023). Doing so could not only lead to a better understanding of potential synergies and trade-offs between NCP (Felipe-Lucia et al., 2018), and the use of anthropogenic capitals but provide relevant insights for governance responses to address unsustainable ways of NCP-co-production at relevant scales of territorial planning (Palomo et al., 2016).
- *Addressing conceptual gaps*. Recent research has employed the concept of NCP co-production across various contexts. However, some conceptual gaps exist. For one, a clear distinction between social capital and governance processes remains challenging due to conceptual overlaps (Brondizio et al., 2009; Palomo et al., 2016). Social capital refers to "diverse social phenomena such as trust, reciprocity and exchange, norms, and networks of interpersonal relationships" (Barnes-Mauthe et al., 2015, p. 393). So far, social capital has been studied in various social-ecological contexts and in relation to governance, especially in the context of managing common-pool resources (see e.g. Auer et al., 2020; Barnes-Mauthe et al., 2015; Brondizio et al., 2009; Pretty, 2003).

Nonetheless, an overlap between social capital and governance exists. Rules and institutions, for example, contribute to the co-production of NCP as social capital, whilst inherent to decision-making processes and governance (Ostrom, 2005). Second, further clarification is needed whether and how the relationship between anthropogenic capitals and NCP is reciprocal. Future research would thus need to investigate whether the provision of co-produced NCP leads to an increase or decrease of certain capital types involved in this process. Opportunities for recreational activities based on landscape beauty could, for example, increase the motivation to invest in tourism infrastructure contributing to better accessibility to nature and its non-material NCP. In turn, recreation can also provide material benefits for local communities. The Mbya Tourism Association around the Iguazu National Park in Argentina is an example of this, as it enables local Indigenous communities to benefit from sustainable tourism (MBYA, 2023). Thus, further research needs to investigate how governance can support reciprocal relationships between anthropogenic capitals and the NCP they co-produce.

- *Accounting for the diversity of stakeholders.* Despite referring to the interaction between nature and people, research has not yet explored the full diversity of actors and stakeholders contributing to and affected by NCP co-production. For instance, it is vital to uncover whether different co-production patterns apply to distinct groups of stakeholders; that is, whether anthropogenic capitals are used differently across stakeholder groups. For instance, Giacommelli et al. asked stakeholders to classify themselves according to their role in NCP co-production (i.e., as user, manager, investigator, interested and negatively influenced), and found that local stakeholders self-identified as users and managers were more strongly linked to human and social capitals in relation to non-material NCP. In contrast, physical and financial capitals were used more for material NCP (Giacomelli et al., under review). Besides, further research is needed to clarify how stakeholder groups across spatial scales are linked to specific anthropogenic capitals since extra-regional have a strong influence on land-use changes, e.g. through investments in real estate, as Marinaro et al. (2022) have shown for the Dry Chaco in Argentina.
- *Understanding the polycentric nature of governing anthropogenic capitals in NCP co-production.* Polycentricity of governance systems and beyond is characterised by a diversity of autonomous decision-making centres across

multiple levels and governance modes (see e.g. Lubell and Morrison, 2021; Ostrom, 1999; Schoon et al., 2015; Stephan et al., 2019). Research on polycentric governance is comprehensive and has focussed on social-ecological interactions and common-pool resources in various ecosystems, for example, forests (Lazdinis et al., 2019), coral reefs (Morrison, 2017), and rivers (Pahl-Wostl and Knieper, 2014). Polycentric governance of ecosystems and NCP is often complex and challenging but offers potential for locally adaptable solutions, as Lazdinis et al. (2019) highlight focusing on forests in the European Union. These forests and their NCP are subject to "around 90 national or sub-national governing bodies" making coordination governance on the EU level difficult (Lazdinis et al., 2019, p. 1746). Hence, future research should investigate how multiple actors across governance levels in polycentric settings influence the use of specific anthropogenic capitals to improve coordination across these levels and facilitate the sustainable co-production of NCP.

- *Dealing with conflicts and power asymmetries*. One major challenge within polycentrically governed systems relates to the role of power (Gadinger and Scholte, 2023; Morrison et al., 2019). Power refers to the "uneven capacity of different actors to influence the goals, process, and outcomes of polycentric governance" (Morrison et al., 2019, p. 2) and has previously been studied regarding its effects on the provision of NCP (Felipe-Lucia et al., 2015; Vallet et al., 2020, 2019). Varying degrees of power influence the governance of NCP as they restrict how stakeholders can obtain benefits from NCP or contribute to their access or management (Martín-López et al., 2019; Vallet et al., 2020). Besides, power asymmetries may hinder the mediation of conflicts regarding NCP and the trade-offs between them (Schoon et al., 2015). A trade-off describes a situation in which management favours the provision of one NCP whilst minimising the provision of another (Felipe-Lucia et al., 2015). Trade-offs and conflicts also exist in using anthropogenic capitals in NCP co-production (Palomo et al., 2016). Conflicts over land tenure, a social capital, or land grabbing by financially powerful multinational corporations are examples of these (Messerli et al., 2014). Besides, substituting one capital type at the expense of others or between capitals of the same type may promote a specific NCP but lead to the loss of other NCP (Palomo et al., 2016). Farming knowledge and physical labour, for example, may be substituted by physical capital in the form of machinery or chemical inputs due to agricultural

intensification, which may result in higher yields but undermines the overall resilience of the agricultural system (Bennett et al., 2021). Moreover, some stakeholders and the capital types that are available to them are particularly vulnerable to the effects of this substitution process. Intensive agriculture, forestry, fisheries, and livestock, for example, not only lead to the loss of biodiversity and the degradation of soils and waters but contribute to the loss of traditional knowledge and livelihoods of Indigenous peoples worldwide (Scheidel et al., 2023). Thus, future research on NCP co-production should acknowledge the large body of literature on power asymmetries and conflicts by aiming to understand how power relations affect the use of specific anthropogenic capitals for a just or potentially unjust provision of NCP.

- *Evidence-based and collaborative approaches to global changes*. Recent studies have called for evidence-based policy-making and collaborative governance (Ansell and Gash, 2007; Emerson and Nabatchi, 2015; Greenwood et al., 2021; Parkhurst, 2017; Tengö et al., 2014). Evidence-based policy-making has been emphasised in the context of science-policy processes, such as in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), in which power imbalances and different epistemological origins of knowledge play a role (Tengö et al., 2014; Turnhout et al., 2012). In this regard, it is relevant to differentiate between knowledge integration, which is about developing synergies and communication across knowledge systems, and knowledge co-production, which refers to the collaborative process of knowledge creation between researchers and a diverse range of societal stakeholders (Agrawal, 1995; Berkes, 2018; Chambers et al., 2021; Jasanoff, 2004; Pohl et al., 2010; Reid et al., 2006). Evidence-based and legitimate knowledge co-production is essential to ensuring transparent and effective territorial governance (IPBES, 2022). Involvement of the public in collaborative processes has been emphasised as a response to the complex management settings of social-ecological systems that are characterised by multiple stakeholders, diverging interests and use of knowledge to support the power imbalances and conflict. Collaboration refers to an intensive form of interaction and negotiation in which the stakeholders actively engage in goal definition, decision-making and implementation of agreed decisions (Gieseke, 2020; Gray, 1989; Peltola et al., 2023). Strategic and structured applications of collaborative processes have been studied as collaborative governance (Ansell and Gash, 2007; Emerson and Nabatchi, 2015; Greenwood et al., 2021; Peltola et al., 2023). The Argentinian

Forest Law is an example of collaborative governance as it was not only implemented with strong bottom-up support from diverse stakeholder groups, such as non-governmental or Indigenous organisations, but explicitly calls for public participation to reach a consensus on conservation measures among stakeholders (Vallejos et al., 2021). So far, few studies on the governance of NCP and ecosystem services, as well as NCP co-production, have investigated the role of evidence-based and collaborative governance (Isaac et al., 2022; Winkler et al., 2021). Thus, future research should focus on the role of society, public managers, stakeholders, or researchers in undertaking knowledge co-production or collaborating to co-create science to overcome knowledge asymmetries and ensure the inclusion of diverse forms of knowledge in the governance of anthropogenic capitals, ecosystems, and their contributions to people.

- *Plural values in governing anthropogenic capitals*. Similarly to governance and institutions, the values stakeholders hold towards nature influence the provision and use of NCP, as the IPBES framework highlights (Díaz et al., 2015). These values have been described as intrinsic, instrumental, and relational (Arias-Arévalo et al., 2017; Chan et al., 2016; Christie et al., 2019; IPBES, 2022). Intrinsic value is based on the notion that nature has the right to exist as an end in itself (Arias-Arévalo et al., 2017; Díaz et al., 2015). Instrumental values relate to the satisfaction of human needs by utilising nature and its NCP (Arias-Arévalo et al., 2017), while relational values describe the manifold interactions in which people "relate with nature and with others" in a meaningful way (Chan et al., 2016, p. 1462). Despite an increase in the scientific literature on plural values (IPBES, 2022; Meyfroidt et al., 2022), decision-making processes have so far neglected the potential of plural values for fostering transformations towards sustainability (Chan et al., 2020), as they have been based on singular, predominantly monetary, valuation approaches (Barton et al., 2022). Thus, recent research has highlighted the importance of integrating plural values into governance and decision-making processes (e.g., Allen et al., 2018; Chan et al., 2016; Hernández-Morcillo et al., 2022; Jacobs et al., 2020; Leventon et al., 2021; Van Noordwijk et al., 2023). Moreover, plural values interact with formal and informal rules as well as with diverse forms of knowledge in shaping the governance of social-ecological systems (Colloff et al., 2017), and, therefore, the governance of capitals underpinning NCP co-production. While recent research has identified how these interactions between values, rules, and knowledge influence the management and governance

of NCP (Topp et al., 2021), future research should focus on how they affect the use of specific anthropogenic capitals to understand better how a plurality of values affects the governance of NCP co-production.

- *Identifying leverage points for sustainable NCP co-production.* Decision-making needs to identify leverage points to transform unsustainable forms of co-production and ensure the long-term provision of NCP (Abson et al., 2017; Hernández-Morcillo et al., 2022; Palomo et al., 2016). Meadows (1999) first described 12 leverage points referring to "places in complex systems where a small shift may lead to fundamental changes in the system as a whole" (Abson et al., 2017, p. 30). 'Shallow' leverage points encompass the 'parameters' of and the 'feedbacks' within a system and are achievable with relative ease but do not lead to systemic change (Abson et al., 2017). 'Deep' leverage points in contrast bring system-wide transformation but are challenging to achieve since they include alterations of the system's 'design' and 'intent' (Abson et al., 2017). Understanding how interconnected leverage-points can be beneficial for a transformation towards sustainable human-nature relationships remains an essential task for future research (Chan et al., 2020; Fischer and Riechers, 2019; Riechers et al., 2021). Leverage points identified by Chan et al. (2020) for a transformation towards sustainability can also be applied to the co-production of NCP as they embrace various anthropogenic capitals. 'Inclusive conservation', for example, represents a deep leverage point as it refers to changes in the system's rules by including Indigenous and local communities into decision-making processes and thus relates to the social capitals of networks and institutions (Chan et al., 2020). 'Technology, innovation, investment' in contrast, relates to physical and financial capital and represents a shallow leverage point as it refers to changes in the systemic parameters (Chan et al., 2020). Moreover, Leventon et al. (2021) argued that embracing plural values of nature (which can be understood as human capital) and creating institutional spaces (which can be understood as social capital), in which we reflect the diversity of values of nature and move away from nature commodification, can act as a deep leverage point for transformation towards sustainability. In addition, various levers representing governance actions, e.g. increasing collaboration across sectors or strengthening adaptive planning, are needed to achieve these leverage points (Chan et al., 2020) and relate to governance modes studied with NCP co-production, such as adaptive-collaborative and scientific-technical governance (Isaac et al., 2022). Considering the expanding

literature on leverage points, future research needs to identify how anthropogenic capitals can serve as shallow and deep leverage points in a transformation towards the sustainable co-production of NCP and analyse which governance responses (levers) are most suitable to achieve them.

3. Concluding remarks

Despite its relevance for the sustainable provision of NCP, the governance of anthropogenic capitals in NCP co-production remains understudied. Research has shown that various governance levels and modes affect the interplay between natural and anthropogenic capitals. Yet, several challenges remain to understand these processes better. For one, progress is needed regarding the conceptual foundations of NCP co-production in order distinguish anthropogenic capitals from the processes governing them clearly. Second, future research should aim to understand better specific contexts in which NCP are co-produced by unravelling the underlying factors influencing the use of specific capitals. This improved understanding includes the synergies and trade-offs between uses of anthropogenic capitals and the NCP they co-produce. Thereby addressing stakeholder's power relations and conflicts and identifying potential leverage points for reaching sustainable ways of co-producing NCP.

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Appendix

Appendix 1: Author contribution statements

Chapter	Journal, impact factor, and publication status	Contributions by authors	Author status and weight	Conference presentations
II	*Advances in Ecological Research* JIF=5.182 (Clarivate 2021) published in 2022	**Roman Isaac** (conceptualisation, data collection, data analysis, writing of original draft), **Jana Kachler** (data collection, review & editing), **Eerika Albrecht** (data collection, writing of original draft, review & editing), **Klara J. Winkler** (data collection, review & editing), **María Felipe-Lucia** (review & editing), **Berta Martín-López** (conceptualisation, data analysis, writing of original draft, review & editing)	Main author (1.0)	*ESP Europe Conference 2021*, Tartu, Estonia and online, June 7-10, 2021 *Biodiversity Exploratories Assembly 2022*, online, February 22-24, 2022 *Science and Research in, for and with UNESCO Biosphere Reserves*, Conference, Schorfheide-Chorin, Germany, May 16-20, 2022
III	*Environmental Science and Policy* JIF=6.0 (Clarivate 2022) published in 2024	**Roman Isaac** (conceptualisation, data collection, data analysis, writing of original draft); **Johanna Hofmann** (data collection, review & editing); **Jana Koegst** (data collection, review & editing); **Christian Schleyer** (review & editing), **Berta Martín-López** (conceptualisation, data analysis, writing of original draft, review & editing)	Main author (1.0)	*Landscape 2021*, online, September 20-22, 2021 *FEdA Conference on Biodiversity and Wellbeing*, online, November 9-11, 2022

III (continued)				*Science and Research in, for and with UNESCO Biosphere Reserves*, Conference, Schorfheide-Chorin, Germany, May 16-20, 2022 *Biodiversity Exploratories Assembly 2023*, Werningerode, Germany, February 21-24, 2023
IV	*People and Nature* JIF=6.1 (Clarivate 2022) in preparation	**Roman Isaac** (conceptualisation, data collection, data analysis, writing of original draft), **Graeme S. Cumming** (review & editing), **María Felipe-Lucia** (review & editing), **Jana Kachler** (data collection), **Berta Martín-López** (conceptualisation, data analysis, writing of original draft, review & editing)	Main author (1.0)	*Congreso Nacional de la Asociacón Española de Ecologia Terrestre* (AEET), National Congress of the Spanish Association for Terrestrial Ecology, University of Almería, Almería, Spain, October 16-20, 2023
V	*Advances in Ecological Research* JIF=5.182 (Clarivate 2021) published in 2023	**Roman Isaac** (conceptualisation, writing of original draft), **Eerika Albrecht** (review & editing, adding to original draft), **María Felipe-Lucia** (review & editing, adding to original draft), **María Piquer-Rodríguez** (review & editing), **Klara J. Winkler** (review & editing), **Berta Martín-López** (conceptualisation, review & editing)	Main author (1.0)	No conference presentations

Appendix 2: Ethics review committee approval

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21. April 2021

Ihr Antrag an den Ethikbeirat der Leuphana Universität Lüneburg EB-Antrag 202103-0-MartinLopez:
Stakeholderbefragung im Forschungsprojekt „Effects of land management on the Supply and Distribution of ecosystem services" (ESuDis)

Sehr geehrte Frau Professorin Martín-López, sehr geehrter Herr Isaac,

Ihr oben genannter Antrag wurde am 10.03.2021 eingereicht und vom Ethikbeirat im Umlaufverfahren beraten.

Mit dem abschließenden Votum beurteilt der Ethikbeirat die Studie als **„ethisch unbedenklich"**.

Wir wünschen Ihrer wissenschaftlichen Arbeit viel Erfolg.

Mit freundlichen Grüßen

Prof. Dr. Dirk Lehr
Vorsitz

Der Bewertung liegen folgende Unterlagen zugrunde:

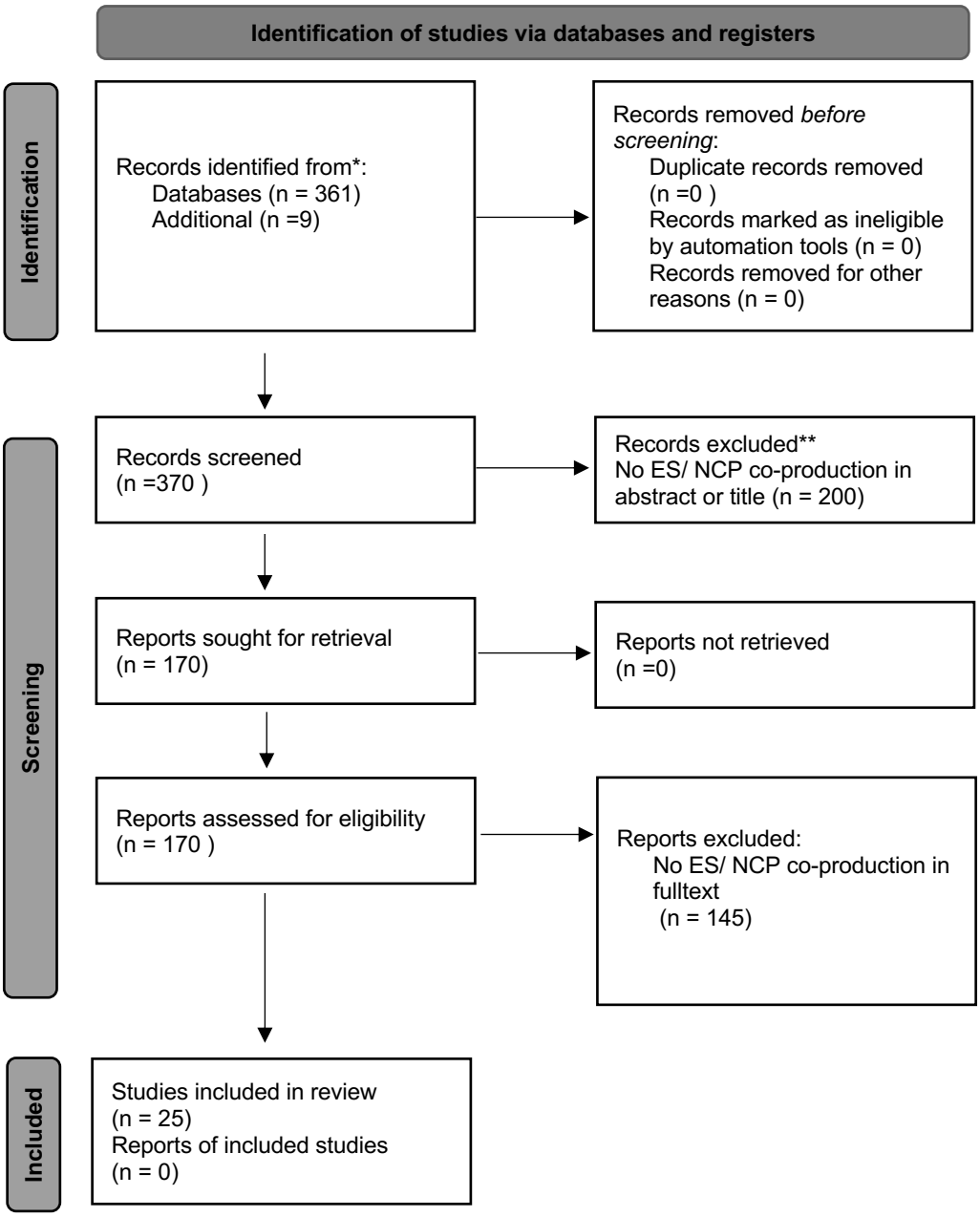
- EB-Antrag mit den folgenden Anlagen
  - Vorhabenbeschreibung
  - Erklärung zum Datenmanagement
  - Muster von Aufklärungs- und Einwilligungstext
  - Umfragetext
  - DFG Drittmittelantrag

Appendix 3: Supplementary Material for Isaac et al. 2022 Governance to manage the complexity of nature's contributions to people co-production (Chapter II)

S1 Text. Literature on ecosystem services and nature's contributions to people co-production

You searched for: TOPIC: ("ecosystem service*" OR "ecosystem function*" OR "ecosystem good*" OR "ecosystem benefit*" OR "environmental service*" OR "environmental function*"
OR "environmental good*" OR "environmental benefit*" OR "natures contribution* to people" OR "nature benefit*" OR "provisioning service*" OR "cultural service*"
OR "regulating service*" OR "supporting service*") AND TOPIC: ("supply" OR "provision" OR "demand" OR "use" OR "value") AND TOPIC: ("anthropogenic capital*" OR "man-made capital*" OR "human-made capital*" OR "human-derived capital*" OR "anthropogenic asset*" OR "man-made asset*" OR "human-made asset*" OR "human-derived asset*"
OR "human capital*" OR "human asset*" OR "technological capital*" OR "technological asset*" OR "manufactured capital*" OR "manufactured asset*" OR "soci* capital*"
OR "soci* factor*" OR "soci* asset*" OR "financial capital*" OR "financial asset*" OR "build capital*" OR "built capital*" OR "physical capital*" OR "physical asset*"
OR "non-natural capital*" OR "non-natural asset*" OR "co-production" OR "coproduction" OR "cocreation" OR "co-creation") AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)
Timespan: 1945-2020. Indexes: SCI-EXPANDED, SSCI.

S2 Figure. PRISMA flow diagram for the selection of publications in the body of literature on NCP co-production.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

For more information, visit: http://www.prisma-statement.org/

S3 Table. List of publications included in the literature review on the governance of NCP co-production.

Number	Body of Literature	Authors	Year	Title	Journal	DOI/URL	Country location	mporal sca	patial scal	Data source	Data type	t co-produ	plicit co-production	to have found co-product
1	ES governance	Gatzweiler F.W.	2006	Organizing a public ecosystem service economy for sustaining biodiversity	ECOLOGICAL ECONOMICS	https://doi.org/10.1016/j.ecolecon.2005.10.01	Ethiopia	n/a	national	both	qualitative	0	1	0
2	ES governance	Ernstson H., Barthel S., Andersson E., Borg	2010	Scale-crossing brokers and network governance of urban ecosystem services	ECOLOGY AND SOCIETY	https://www.jstor.org/stable/26268215	Sweden	multiple pc	local	secondary	both	0	1	0
3	ES governance	Gómez-Baggethun E., Kelemen E., Martín	2013	Scale Misfit in Ecosystem Service Governance as a Source of Environmental C	SOCIETY AND NATURAL RESOURCES	https://doi.org/10.1080/08941920.2013.8208	Spain	single point	regional	both	both	1	0	1
4	ES governance	Knüppe K., Pahl-Wostl C.	2013	Requirements for adaptive governance of groundwater ecosystem services:	REGIONAL ENVIRONMENTAL CHANGE	10.1007/s10113-012-0312-7	multiple	range	regional	both	qualitative	0	1	0
5	ES governance	Morán-Ordóñez A., Bugter R., Suárez-Seo	2013	Temporal Changes in Socio-Ecological Systems and Their Impact on Ecosyste	ECOSYSTEMS	https://doi.org/10.1007/s10021-013-9649-0	Spain	multiple pc	regional	secondary	qualitative	0	1	0
6	ES governance	Young R.F., McPherson E.G.	2013	Governing metropolitan green infrastructure in the United States	LANDSCAPE AND URBAN PLANNING	https://doi.org/10.1016/j.landurbplan.2012.05	USA	single point	local	primary	qualitative	0	1	0
7	ES governance	Kaye-Zwiebel E., King E.	2014	Kenyan pastoralist societies in transition: Varying perceptions of the value of	ECOLOGY AND SOCIETY	https://www.jstor.org/stable/26269603	Kenya	single point	local	primary	both	0	1	0
8	ES governance	Farhad S., Gual M.A., Ruiz-Ballesteros E.	2015	Linking governance and ecosystem services: The case of Isla Mayor (Andalus	LAND USE POLICY	https://doi.org/10.1016/j.landusepol.2015.01.	Spain	range	local	both	qualitative	0	1	0
9	ES governance	Felipe-Lucia M.R., Martín-López B., Lavore	2015	Ecosystem services flows: Why stakeholders' power relationships matter	PLOS ONE	https://doi.org/10.1371/journal.pone.0132232	Spain	multiple pc	regional	both	both	1	0	1
10	ES governance	Outeiro L., Gajardo C., Oyarzo H., Ther F.,	2015	Framing local ecological knowledge to value marine ecosystem services for t	ECOSYSTEM SERVICES	https://doi.org/10.1016/j.ecoser.2015.04.004	Chile	single point	regional	primary	both	0	1	0
11	ES governance	Knüppe K., Pahl-Wostl C., Vinke-de Kruijf J.	2016	Sustainable Groundwater Management: A Comparative Study of Local Policy	ENVIRONMENTAL POLICY AND GOVERNANCE	https://doi.org/10.1002/eet.1693	multiple	single point	regional	both	qualitative	0	1	0
12	ES governance	Schermer M., Darnhofer I., Daugstad K., G	2016	Institutional impacts on the resilience of mountain grasslands: An analysis ba	LAND USE POLICY	https://doi.org/10.1016/j.landusepol.2015.12.	multiple	single point	regional	both	both	0	1	0
13	ES governance	Garrido P., Elbakidze M., Angelstam P.	2017	Stakeholders' perceptions on ecosystem services in Östergötland's (Sweden)	LANDSCAPE AND URBAN PLANNING	https://doi.org/10.1016/j.landurbplan.2016.08	Sweden	single point	regional	primary	qualitative	0	1	0
14	ES governance	Garrido P., Elbakidze M., Angelstam P., Pli	2017	Stakeholder perspectives of wood-pasture ecosystem services: A case study i	LAND USE POLICY	https://doi.org/10.1016/j.landusepol.2016.10.	Spain	single point	regional	primary	qualitative	1	0	1
15	ES governance	Mannetti L.M., Göttert T., Zeller U., Esler	2017	Expanding the protected area network in Namibia: An institutional analysis	ECOSYSTEM SERVICES	https://doi.org/10.1016/j.ecoser.2017.08.008	Namibia	single point	regional	primary	qualitative	0	1	0
16	ES governance	Tikkanen J., Hokajärvi R., Hujala T., Kurttila	2017	Ex ante evaluation of a PES system: Safeguarding recreational environments	JOURNAL OF RURAL STUDIES	https://doi.org/10.1016/j.jrurstud.2017.03.011	Finland	single point	local	both	both	0	1	0
17	ES governance	Ward C., Stringer L., Holmes G.	2018	Changing governance, changing inequalities: Protected area co-managemer	ECOSYSTEM SERVICES	https://doi.org/10.1016/j.ecoser.2018.01.014	Madagascar	single point	local	primary	both	0	1	0
18	ES governance	Dietze V., Hagemann N., Jürges N., Bartke	2019	Farmers consideration of soil ecosystem services in agricultural managemen	LAND USE POLICY	https://doi.org/10.1016/j.landusepol.2018.11.	Germany	single point	regional	primary	qualitative	0	1	0
19	ES governance	Aguilera, Moisés A., Jan Tapia, Camila Gall	2020	Loss of coastal ecosystem spatial connectivity and services by urbanization: N	JOURNAL OF ENVIRONMENTAL MANAGEMENT	https://doi.org/10.1016/j.jenvman.2020.1112	Chile	single point	local	primary	qualitative	0	1	0
20	ES governance	Larson, Kelli L., Riley Andrade, Kristen C. N	2020	Municipal regulation of residential landscapes across US cities: Patterns and	JOURNAL OF ENVIRONMENTAL MANAGEMENT	https://doi.org/10.1016/j.jenvman.2020.1111	USA	single point	local	primary	qualitative	0	1	0
21	ES governance/ NCP co-production	Lavorel, Sandra, Bruno Locatelli, Matthew	2020	Co-producing ecosystem services for adapting to climate change	PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCI	https://doi.org/10.1098/rstb.2019.0119	multiple	single point	regional	secondary	qualitative	1	0	1
22	NCP co-production	Fischer, Anke, and Antonia Eastwood	2016	Coproduction of ecosystem services as human-nature interactions-Ananalyti	LAND USE POLICY	https://doi.org/10.1016/j.landusepol.2015.12.	UK	single point	regional	primary	qualitative	1	0	1
23	NCP co-production	Garcia-Llorente, Marina, Irene Iniesta-Ara	2015	Biophysical and sociocultural factors underlying spatialtrade-offs of ecosyste	ECOLOGY AND SOCIETY	http://dx.doi.org/10.5751/ES-07785-200339	Spain	single point	regional	both	quantitativ	1	0	1
24	NCP co-production	Hipolito, Juliana, Blandina Felipe Viana, an	2016	The value of pollinator-friendly practices: Synergiesbetween natural and ant	BASIC AND APPLIED ECOLOGY	https://doi.org/10.1016/j.baae.2016.09.003	Brazil	single point	regional	both	quantitativ	0	1	0
25	NCP co-production	Jackson, L.E., M.M. Pulleman, L. Brussaard	2012	Social-ecological and regional adaptation of agrobiodiversity management a	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND PO	https://doi.org/10.1016/j.gloenvcha.2012.05.0	multiple	range	regional	both	both	0	1	0
26	NCP co-production	Lavelle, Patrick, Sylvain Dolédec, Xavier Ar	2016	Unsustainable landscapes of deforested Amazonia: An analysis of the relatio	GLOBAL ENVIRONMENTAL	https://doi.org/10.1016/j.gloenvcha.2016.04.0	Brazil; Colombia	single point	regional	primary	both	0	1	0
27	NCP co-production	Malinga, Rebecka Henriksson, Graham P.	2018	On the other side of the ditch: Exploring contrasting ecosystem service copro	CHANGE-HUMAN AND POLICY DIMENSIONS	https://doi.org/10.5751/ES-10380-230409	South Africa	single point	regional	both	both	1	0	1
28	NCP co-production	Quintas-Soriano, Cristina, Jodi S. Brandt, Ka	2018	Social-ecological systems influence ecosystem service perception: A Program	ECOLOGY AND SOCIETY	https://doi.org/10.5751/ES-10226-230303	multiple	single point	regional	both	both	0	1	0
29	NCP co-production	Torralba, Mario, Elisa Oteros-Rozas, Gerar	2018	Exploring the Role of Management in the Coproduction of Ecosystem Service	ECOLOGY AND SOCIETY	https://doi.org/10.1016/j.rama.2017.09.001	Spain	single point	regional	primary	quantitativ	1	0	1
30	NCP co-production	Vialatte, Aude, Cecile Barnaud, Julien Blan	2019	A conceptual framework for the governance ofmultiple ecosystem services i	RANGELAND ECOLOGY	https://doi.org/10.1007/s10980-019-00829-4	France	single point	regional	both	qualitative	1	0	0
31	NCP co-production	López-Santiago, César A., Elisa Oteros-Roz	2014	Using visual stimuli to explore the social perceptions of ecosystem services in	& MANAGEMENT	http://dx.doi.org/10.5751/ES-06401-190227	Spain	single point	regional	primary	quantitativ	0	1	0
32	NCP co-production	Martín-López, Berta, Irene Iniesta-Arandia	2012	Uncovering Ecosystem Service Bundles through Social Preferences.	LANDSCAPE ECOLOGY	https://doi.org/10.1371/journal.pone.0038970	Spain	single point	regional	primary	quantitativ	0	1	0
33	NCP co-production	Rojas, Octavio, María Zamorano, Katia Sae	2017	Social Perception of Ecosystem Services in a Coastal Wetland Post-Earthquak	ECOLOGY AND SOCIETY	https://doi.org/10.3390/su9111983	Chile	single point	local	primary	quantitativ	0	1	0
34	NCP co-production	Hicks, Christina C., and Joshua E. Cinner.	2014	Social, institutional, and knowledge mechanisms mediate diverse ecosystem	PLOS ONE	https://doi.org/10.1073/pnas.1413473111	Kenya; Madagascar; Seyche	single point	multinatio	primary	both	0	1	0
35	NCP co-production	Bravo-Monroy, L., J. Tzanopoulos, and S.G.	2015	Ecological and social drivers of coffee pollination in Santander, Colombia	SUSTAINABILITY	https://doi.org/10.1016/j.agee.2015.06.007	Colombia	single point	farm	primary	both	0	1	0
36	NCP co-production	Auer, A., N. Maceira, and L. Nahuelhual	2017	Agriculturisation and trade-offs between commodity production and cultura	PNAS	https://doi.org/10.1016/j.jrurstud.2017.05.011	Argentina	multiple pc	regional	primary	qualitative	1	0	1
37	NCP co-production	Scholte, Samantha S. K., Maya Todorova, A	2016	Public Support for Wetland Restoration: What is the Link With Ecosystem Ser	AGRICULTURE, ECOSYSTEMS AND ENVIRONMENT	10.1007/s13157-016-0755-6	Bulgaria	single point	regional	primary	quantitativ	0	1	0
38	NCP co-production	avorel, Sandra, Bruno Locatelli, Matthew J	2020	Ecosystem services, well-being benefits and urbanization associations in a Sm	JOURNAL OF RURAL STUDIES	https://doi.org/10.1002/pan3.10180	Solomon Islands	single point	local	primary	both	0	1	0
39	NCP co-production	Julian, Jason, Graham Daly, and Russell We	2018	University Students' Social Demand of a Blue Space and the Influence of Life	WETLANDS	https://doi.org/10.3390/su10093178	USA	single point	local	primary	quantitativ	0	1	0
40	NCP co-production	Brown, Jeffrey A., Kelli L. Larson, Susannah	2020	Influences of Environmental and Social Factors on Perceived Bio-Cultural Ser	PEOPLE AND NATURE	https://doi.org/10.3389/fevo.2020.569730	USA	single point	local	secondary	quantitativ	0	1	0
41	NCP co-production	Muhamad, Dendi, Satoru Okubo, Koji Hara	2014	Living close to forests enhances people's perception of ecosystem services in	SUSTAINABILITY	https://doi.org/10.1016/j.ecoser.2014.04.003	Indonesia	single point	regional	primary	quantitativ	0	1	0
42	NCP co-production	Zeweld, W. Zeweld, Woldegebrial, Guido V	2019	Sustainable agricultural practices, environmental risk mitigation and livelihoo	FRONTIERS IN ECOLOGY AND EVOLUTION	https://doi.org/10.1016/j.landusepol.2019.01.	Ethiopia	single point	farm	primary	quantitativ	0	1	0
43	NCP co-production	Nagendra, Harini, and Elinor Ostrom	2014	Applying the social-ecological system framework to the diagnosis of urban la	ECOSYSTEM SERVICES	http://dx.doi.org/10.5751/ES-06582-190267	India	single point	local	primary	quantitativ	0	1	0
44	NCP co-production	Yang, Wanni, and Lin Zhen	2020	Household perceptions of factors that affect food consumption in grassland a	LAND USE POLICY	https://doi.org/10.1088/1748-9326/abc0b9	China	single point	regional	primary	both	0	1	0
45	NCP co-production	Lindsay, Amanda R., James N. Sanchirico, T	2020	Evaluating sustainable development policies in rural coastal economies	ECOLOGY AND SOCIETY	https://doi.org/10.1073/pnas.2017835117	Indonesia	multiple pc	regional	primary	quantitativ	0	1	0

S4 Table. Metadata sheet for the systematic literature review on the governance of nature's contributions to people (NCP) co-production containing the codes and sub-codes used.

	Sub-code	Description	Definition (if applicable)	Selection
1) general paper info	paper ID	identification number of the publication		number (continuous)
	ID co-prod. review	identification number of the publication in co-production review		number
	ID governance review	identification number of the publication in old governance and ES database		number
	coder	person coding the paper		JK;RI;MFL;BML; EA; KW
	authors	authors		text
	year	year of the publication		text
	title	title of the publication		text
	journal	journal in which the study is published		text
	document type	type of the publication		peer-reviewed article; book chapter
	type of study	type of the study		case study; systematic review; expert review; n/a
2) study location	country location	country where case-study takes place		text
3) temporal scale	temporal scale	temporal scale at which study takes place		single point; multiple points; range; n/a
4) spatial scale	spatial scale	which spatial level is studied		global; continent; multinational; national; landscape; municipality; n/a
5) landscape type	landscape	which landscape is studied		forest; non-woody natural vegetation; grassland; marine and coastal; wetland; mountain; cropland; urban green space; n/a
6) data & methods	data source	source of data		primary; secondary; both, n/a
	data type	type of data		quantitative; qualitative; both; n/a

	data collection methods	methods of data collection		text
	analytical methods	methods of data analysis		text
7) co-production general	claim to have found co-production	authors claim to have found co-production		0= no; 1= yes
	explicit co-production	study uses the concept of co-production explicitly		0= no; 1= yes
	implicit co-production	study uses the concept of co-production implicit		0= no; 1= yes
	Polycentric governance	study addresses several governance levels	*"Polycentric*: connotes multiple centres of decision-making authority which are de jure independent or de facto autonomous of each other. *Polycentric Governance*: governance that has polycentric attributes, where governance is a process by which the repertoire of rules, norms, and strategies that guide behaviour within a given realm of policy interactions are formed, applied, interpreted, and reformed." (Stephan et al., 2019, p. 40)	0= no; 1= yes
	comments	other remarks or comments		text
8) NCP categories	NCP category	category to which the co-produced NCP belongs		provisioning; regulating; cultural; multiple
	material NCP	sub-category to which the NCP belongs to in case that it is a material (defined in previous column) (see sub-categories on the right)	"physical substances, objects, or materials from nature which people use to consume to live", such as the provision of food or building materials (Hill et al., 2021, p. 911)	energy; food and feed; materials, companionship, and labour; medicinal, biochemical, and genetic resources; other provisioning service

	regulating NCP	sub-category to which the NCP belongs to in case that it is a regulating NCP (defined in previous column) (see sub-categories on the right)	"modify environmental conditions experienced by people, and/or sustain and/or regulate the generation of material and non-material contributions" (Díaz et al., 2018, p. 5)	habitat; pollination; air quality; climate; ocean acidification; freshwater quantity; freshwater quality; soils and sediments; hazards; detrimental organisms and biological processes; other regulating service
	non-material NCP	sub-category to which the NCP belongs to in case that it is a non-material NCP (defined in previous column) (see sub-categories on the right)	Non-material NCP entail "nature's effects on subjective or psychological aspects underpinning people's quality of life" on both an individual as well as at societal level (Hill et al., 2021, p. 911).	learning and inspiration; physical and psychological experiences; supporting identities; maintenance of options; other cultural service
	NCP (in words)	describe NCP in words		text
9) capital types	natural capital indicator	describe the natural capital underpinning the NCP in words	Natural capital compromises the stock of natural resources and ecosystem functions that independently or combined with anthropogenic capitals provide ecosystem services (Goodwin, 2003; Palomo et al., 2016).	text
	human capital category	category to which human capital belongs to (if applicable)	Human capital refers to people's capabilities including health, informal knowledge, formal knowledge, skills, motivation, and labour that can yield a flow of ecosystem services (Goodwin, 2003; Palomo et al., 2016).	health; formal knowledge; informal knowledge; skills; motivation; manual labour; other human capital
	social capital category	category to which social capital belongs to (if applicable)	Social capital includes all intangible assets associated with interactions between people including formal and informal networks, trust, and formal and informal institutions required for enhancing the flow of ecosystem services. (Palomo et al., 2016)	networks; trust; formal institutions; informal institutions; other social capital

	physical capital category	category to which physical capital belongs to (if applicable)	Physical capital refers to technological or manufactured assets that contribute to the flow of ecosystem services (Goodwin, 2003; Palomo et al., 2016; Pretty, 2003).	tools and machinery; infrastructure and built capital; other physical capital
	financial capital	if co-production involves financial capital	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 that contribute to the flow of ecosystem services. (Palomo et al., 2016)	0= no; 1= yes
10) general info on governance	governance level	level at which governance is executed	"At the level of governance, the delivery of ecosystem services is arbitrated by the suite of institutions in place, such as land tenure, communal rules and norms, and taxes and subsidies" (Malinga et al., 2018, p. 8).	municipal; regional (e.g. county or shire); sub-national (e.g. federal state); national; supra-national; international
	governance level indicator	indicator on how the level was identified		text
	governance affecting capitals	whether governance affects capitals		human capital; social capital; physical capital; financial capital; multiple
	governance affecting NCP	whether governance affects ecosystem services		provisioning; regulating; cultural; multiple
	governance suggestion	governance is suggested (hypothetical) instead of measured		0= no; 1= yes
	formal governance	governance with involvement of formal institutions and formal rules		0= no; 1= yes
	formal governance indicator	indicator on how the formal governance was identified	"formally sanctioned rules such as laws, property rights, and bureaucratic functions of	text

			government" (Gómez-Baggethun et al., 2013, p. 1212)	
	informal governance	governance with involvement of informal institutions e.g., traditions or customary right, informal groups	"communal lands, nonformal institutions such as traditions and customary right, established on the basis of local and traditional ecological knowledge" (Gómez-Baggethun et al., 2013, p. 1212)	0= no; 1= yes
	informal governance indicator	indicator on how the informal governance was identified		text
11) governance modes	hierarchical governance	Top-down formal governance steering lower entities	**Hierarchical governance** concerns regulations that influence NCP as well as the other modes of governance (Primmer et al., 2015). In contrast to collaborative governance, hierarchical governance is executed by state actors through formal institutions. Formal institutions exist mainly in the form of policies (e.g., frameworks, laws, regulations) that directly affect NCP or the other governance modes. As interdependencies between policies across governance levels exist, hierarchical governance is often studied in multi-level contexts. Governance of NCP is therefore often linked to scale mismatches (Borgström et al., 2006; Winkler et al., 2021). Scale mismatches occur when ecosystem boundaries do not match with the borders of administrative units. A positive example is the Water Framework	0= no; 1= yes

		Directive, which was the first European Union directive using a natural unit (water catchments) for governance, rather than administrative units such as counties (Moss, 2012).	
hierarchical governance indicator	indicator on how hierarchical governance was identified		text
scientific technical governance	governance based on scientific arguments or involving consultation of scientists at the science policy interface	**Scientific-technical governance** refers to the processes of decision making based on scientific and technical arguments (Primmer et al., 2015). Experts who are not necessarily scientists influence decision play a vital role in this process. The underlying expectation for scientific-technical governance is that effective dissemination of scientific knowledge leads to better governance (Huth and Possingham, 2011; Sutherland et al., 2004). Land-use planning serves as an example for this governance mode as it incorporates scientific arguments when making decisions about potential trade-offs between NCP (Paavola and Hubacek, 2013).	0= no; 1= yes
scientific technical governance indicator	indicator on how scientific technical governance was identified		text
collaborative governance	bottom-up based governance seeking to overcome conflicts	**Collaborative governance** stresses the importance of collective learning	0= no; 1= yes

		through stakeholder inclusion in participatory processes	and bottom-up participatory processes that embrace diverse stakeholder perspectives (Primmer et al., 2015). Moreover, collaborative governance is best executed when based open and transparent processes to collective problem-solving (Newig and Fritsch, 2009). Participatory processes are often considered to contribute positively to ecological outcomes (Bäckstrand et al., 2010).	
	collaborative governance indicator	indicator on how collaborative governance was identified		text
	adaptive governance	governance based on the learning about ever changing circumstances	**Adaptive governance** tries to increase the responsive capacity to changing circumstances, including changing societal values (Burkhard et al., 2012). Examples are stewardships approaches to ecosystems (Chapin III et al., 2015; Olsson et al., 2008), or approaches that promote local learning (Cork et al., 2006).	0= no; 1= yes
	adaptive governance indicator	indicator on how adaptive governance was identified		text
	governing strategic behaviour	strategic planning of actions against certain forms of policies or governance	**Governing of strategic behaviour** features the potential of governance arrangements and the interactions between them to be transformative (Primmer et al., 2015). It refers to market-based or commercial approaches. This implies the aim to	0= no; 1= yes

			influence policy-making processes through lobbying with the goal of affecting policies and protect certain interests (Newig and Fritsch, 2009; Primmer et al., 2015). Besides, governing of strategic behaviour can nudge behaviour in a wanted direction (Primmer, 2011). Payments for ecosystem services are a common example for governing of strategic behaviour often referred to in the literature (see e.g. Börner et al., 2010; Rival, 2010; Van Hecken and Bastiaensen, 2010).	
	governing strategic behaviour indicator	indicator on how governing strategic behaviour was identified		text
	governing strategic behaviour by whom	who agitates against certain forms of governance e.g. a certain policy		text
	governing strategic behaviour against	against which form of governance is action taken		text
	other forms of governance	other forms of governance not included above		open
12) general comments	general comments	general comments about the publication		open

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Appendix 4: Supplementary material for Isaac et al. (2024) Governing anthropogenic assets for nature's contributions to people in forests: a policy document analysis (Chapter III)

Appendix A. Table Defining anthropogenic capitals that underpin nature's contributions to people co-production. Adapted from Isaac et al., (2022) and based on Palomo et al. (2016).

Type of anthropogenic capital	*Definition*	*Forest related examples*
Human capital	Includes people's capabilities such as health, knowledge, skills, motivation, and labour that contribute to the provision of NCP.	Forest management, forestry specific knowledge, habitat specific knowledge.
Social capital	Any form of interaction between people through networks, trust or within or between institutions that supports the provision of NCP.	Forestry associations that organise forest management and timber harvest. Formal institutions, such as laws, that regulate the use and management of forests and their products.
Physical capital	Manufactured or technological capitals that are used to provide NCP. Infrastructure and built capital that is used to access NCP.	Machinery and tools used in forestry such as chainsaws, harvesters, trucks, or fences. Logging roads or footpaths.
Financial capital	Any form of financial stream in the form of savings, credits, subsidies, direct payments or revenue that enables the use of other anthropogenic capitals and thereby underpins the provision of NCP.	Governmental direct payments to leave deadwood in forests. Bank loans to buy machinery.

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Appendix B. Modes of governing nature's contributions to people. Based on Primmer et al. (2015) and adapted from Isaac et al. (2022, p. 8).

Hierarchical governance concerns regulations that influence NCP and the other modes of governance (Primmer et al., 2015). In contrast to collaborative governance, hierarchical governance is executed by state actors through formal institutions. Formal institutions exist mainly in the form of policies (e.g., frameworks, laws, regulations) that directly affect NCP or the other governance modes. As interdependencies between policies across governance levels exist, hierarchical governance is often studied in multi-level contexts. Therefore, governance of NCP is often linked to scale mismatches (Borgström et al., 2006; Winkler et al., 2021). Scale mismatches occur when ecosystem boundaries do not match with the administrative units' borders. A positive example is the Water Framework Directive, the first European Union directive using a natural unit (water catchments) for governance, rather than administrative units such as counties(Moss, 2012).

Scientific-technical governance refers to decision-making based on scientific and technical arguments (Primmer et al., 2015). Experts, who are not necessarily scientists, influence decision-making, play a vital role in this process. The underlying expectation for scientific-technical governance is that effective dissemination of scientific knowledge leads to better governance (Huth and Possingham, 2011; Sutherland et al., 2004). Land-use planning serves as an example for this governance mode as it incorporates scientific arguments when making decisions about potential trade-offs between NCP (Paavola and Hubacek, 2013).

Collaborative governance stresses the importance of collective learning and bottom-up participatory processes that embrace diverse stakeholder perspectives (Primmer et al., 2015). Moreover, collaborative governance is best executed when based on open and transparent processes to collective problem-solving (Newig and Fritsch, 2009). Participatory processes are often considered to contribute positively to ecological outcomes (Bäckstrand et al., 2010).

Adaptive governance responds to changes in the social or ecological system and is often organised polycentrically by involving various decision-making centres (Folke et al., 2005). It is used to increase the responsive capacity to changing circumstances, including changing societal values (Burkhard et al., 2012). Examples are stewardship approaches to ecosystems (Chapin III et al., 2015; Olsson et al., 2008) or approaches that promote local learning (Cork et al., 2006).

Governing of strategic behaviour features the potential of governance arrangements and the interactions between them to be transformative (Primmer et al., 2015). It refers to market-based or commercial approaches. This implies the aim to influence policy-making processes through lobbying with the goal of affecting policies and protecting certain interests (Newig and Fritsch, 2009; Primmer et al., 2015). Besides, governing of strategic behaviour can nudge behaviour in a wanted direction (Primmer, 2011). Payments for ecosystem services are a typical example of governing strategic behaviour often referred to in the literature (see e.g., Börner et al., 2010; Rival, 2010; Van Hecken and Bastiaensen, 2010).

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Appendix C. Databases and websites used to identify policy documents

Institution	*Database/ Website*	*URL*
European Union	EUR-Lex: Access to European Law	https://eur-lex.europa.eu/homepage.html
Federal Ministry of Justice (Bundesjustizministerium)	Laws on the internet (Gesetze im Internet)	https://www.gesetze-im-internet.de/
State of Brandenburg (Land Brandenburg)	Regulation search (Vorschriftensuche)	https://bravors.brandenburg.de/de/vorschriften_schnellsuche
Free State of Thuringia (Freistaat Thüringen)	Online Administration Thuringia (Online Verwaltung Thüringen)	https://landesrecht.thueringen.de/bsth/search
State of Baden-Württemberg (Land Baden-Württemberg)	State law BW Citizen Service (Landesrecht BW Bürgerservice)	https://www.landesrecht-bw.de/jportal/portal/page/bsbawueprod.psml
Biosphere Reserve Schorfheide-Chorin (Biosphärenreservat Schorfheide-Chorin)	Biosphere Reserve Website	https://www.schorfheide-chorin-biosphaerenreservat.de/
Biosphere Reserve Schwäbische Alb (Biosphärengebiet Schwäbische Alb)	Biosphere Reserve Website	https://www.biosphaerengebiet-alb.de/
National Park Hainich	National Park Website	https://www.nationalpark-hainich.de/de/nationalpark/nationalpark-hainich.html
State Firm Forest Brandenburg (Landesbetrieb Forst Brandenburg)	Website	https://forst.brandenburg.de/lfb/de/
Thuringia Forest (Thüringen Forst)	Website	https://www.thueringenforst.de
Forest BW (Forst BW)	Website	https://www.forstbw.de/startseite/
Landesforstverwaltung Baden-Württemberg	Website	https://www.landesforstverwaltung-bw.de/startseite

Appendix D. Overview of policies coded. Sorted by governance levels and policy field.

Governance level	*Shortened policy title and year of version coded (English translation in Italics)*	*Abbrevia-tion/ Number*	*Full title*	*Policy field*	*Type of document*	*Language coded in*	*Num-ber of pages*
European Union	Biodiversity Strategy (2020)	(COM (2020) 380 final)	Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions EU Biodiversity Strategy for 2030 Bringing Nature back into our Lives	Biodiversity conservation	Communication	English	27
	Habitats Directive (1992)	(92/43/E WG)	(92/43/EWG) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora	Biodiversity conservation	Directive	German	44
	Birds Directive (2009)	(2009/147 /EC)	Birds Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds	Biodiversity conservation	Directive	English	19
	Harmful Plants Directive	(2000/29/ EC)	Council Directive 2000 29 EC of 8 May 2000 against organisms harmful to plants or plant products	Biodiversity conservation	Directive	English	112

Regulation on Invasive Alien Species (IAS) (2014)	(2014/1143/EU)	Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species	Biodiversity conservation	Regulation	English	21
Forest Strategy for 2030	(COM(2021) 572 final)	Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions New EU Forest Strategy for 2030	Forestry	Communication	English	30
Forest Reproductive Material Directive (1999)	(1999/105/EC)	Council Directive 1999/105/EC of 22 December 1999 on the marketing of forest reproductive material	Forestry	Directive	English	24
Timber and Timber Trade Regulation (2010)	(2010/995/EU)	Regulation (EU) No 995 2010 of the European Parliament and of the Council of 20 October 2010 timber and timber products	Forestry	Regulation	English	12
LULUCF Regulation (2018)	(2018/841 / EU)	Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU (Text with EEA relevance)	Climate	Regulation	English	25

Bioeconomy Strategy (2018)		European Commission 2018 A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment Updated Bioeconomy Strategy	Bioeconomy	Strategy	English	107
Renewable Energy Directive (2018)	(2018/2001/ EU)	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources	Energy	Directive	English	128
Direct Payments Regulation (2014)	(2014/639/EU)	Commission delegated regulation (EU) No 639/2014 of 11 March 2014 supplementing Regulation (EU) No 1307/2013 of the European Parliament and of the Council establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and amending Annex X to that Regulation	Agriculture	Regulation	English	47
EU Green Deal (2019)	(COM(2019) 640 final)	Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions the European Green Deal	Bioeconomy	Communication	English	28

	EAFRD Funding Regulation (2013)	(2013/1305/EU)	Regulation (Eu) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005	Rural development	Regulation	English	62
Germany	Gesetz über Naturschutz und Landschaftspflege (2009), *Nature Protection and Landscape Maintenance Law*	BNatSchG	Gesetz über Naturschutz und Landschaftspflege	Biodiversity conservation	Law	German	67
	Bundesartenschutzverordnung (2005), *Federal Species Protection Regulation*	BArtSchV	Verordnung zum Schutz wild lebender Tier- und Pflanzenarten (Bundesartenschutzverordnung)	Biodiversity conservation	Regulation	German	73
	Aktionsprogramm Insektenschutz (2019), *Action Programme for Pollinator Protection*		Aktionsprogramm Insektenschutz	Biodiversity conservation	Strategy	German	68
	Nationale Strategie zur biologischen Vielfalt (2007), *National Strategy on Biological Diversity*		Nationale Strategie zur biologischen Vielfalt - Kabinettsbeschluss vom 7. November 2007	Biodiversity conservation	Strategy	German	180
	Bundeswaldgesetz (1975), *Federal Forest Law*	BWaldG	Gesetz zur Erhaltung des Waldes und zur Förderung der Forstwirtschaft (Bundeswaldgesetz)	Forestry	Law	German	13
	Forstvermehrungsgut-gesetz (2002), *Forest Propagation Goods Law*	FoVG	Forstvermehrungsgutgesetz	Forestry	Law	German	9

	Waldstrategie 2020 (2011), *German Forest Strategy 2020*		Waldstrategie 2020 - Nachhaltige Waldbewirtschaftung – eine gesellschaftliche Chance und Herausforderung	Forestry	Strategy	German	36
	Waldstrategie 2050 (2020), *German Forest Strategy 2050*		Waldstrategie 2050 Nachhaltige Waldbewirtschaftung – Herausforderungen und Chancen für Mensch, Natur und Klima	Forestry	Strategy	German	56
	Forstschäden-Ausgleichgesetz (1969), Forest Damage Compensation Law	ForstSch AusglG	Gesetz zum Ausgleich von Auswirkungen besonderer Schadensereignisse in der Forstwirtschaft (Forstschäden-Ausgleichgesetz)	Forestry	Law	German	4
	Naturwaldentwicklung im Nationalen Naturerbe (2017), *Natural Forest Development in National Natural Heritage Sites*		Naturwaldentwicklung im Nationalen Naturerbe Waldentwicklungskonzept für die Naturerbeflächen des Bundes	Forestry		German	10
	Bundesjagdgesetz (1976), *Federal Hunting Law*	BJagdG	Bundesjagdgesetz	Other	Law	German	20
	Rahmenplan der Gemeinschafts-aufgabe „Verbesserung der Agrarstruktur und des Küstenschutzes“ 2021-2024 (2020), *Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024*	Rahmenplan GAKG	Rahmenplan der Gemeinschaftsaufgabe „Verbesserung der Agrarstruktur und des Küstenschutzes“ 2021-2024	Rural development	Master Plan	German	156

Brandenburg	Verordnung über die Festsetzung von Naturschutzgebieten und einem Landschaftsschutzgebiet von zentraler Bedeutung mit der Gesamtbezeichnung „Biosphärenreservat Schorfheide-Chorin“ (1990), *Regulation on the Biosphere Reserve Schorfheide-Chorin*		Verordnung über die Festsetzung von Naturschutzgebieten und einem Landschaftsschutzgebiet von zentraler Bedeutung mit der Gesamtbezeichnung „Biosphärenreservat Schorfheide-Chorin“ vom 12. September 1990 (/ GBl. 1990 SDr., [Nr. 1472], S., GVBl. 2008 II S.327)	Biodiversity conservation	Regulation	German	12
	Pflege und Entwicklungsplan für das Biosphärenreservat Schorfheide-Chorin (1997), *Maintenance and Development Plan for the Biosphere Reserve Schorfheide-Chorin*		Pflege und Entwicklungsplan für das Biosphärenreservat Schorfheide-Chorin	Biodiversity conservation	Management Plan	German	223
	Verwaltungsvorschrift zum Vertragsnaturschutz im Wald (2020)	VV-VN-Wald	Verwaltungsvorschrift zum Vertragsnaturschutz im Wald	Biodiversity conservation	Regulation	German	31

	Brandenburgisches Ausführungsgesetz zum Bundesnaturschutzgesetz (2013), *Brandenburg Nature Protection Law*	BbgNatSchG	Brandenburgisches Ausführungsgesetz zum Bundesnaturschutzgesetz (Brandenburgisches Naturschutzausführungsgesetz - BbgNatSchAG) vom 21. Januar 2013 (GVBl.I/13, [Nr. 3], S., ber. GVBl.I/13 [Nr. 21]) zuletzt geändert durch Artikel 1 des Gesetzes vom 25. September 2020 (GVBl.I/20, [Nr. 28])	Biodiversity conservation	Law	German	29
	Verordnung über das Naturschutzgebiet „Naturentwicklungsgebiet Redernswalde“ (2008), Regulation on the Nature Protection Area Redernswalde		Verordnung über das Naturschutzgebiet „Naturentwicklungsgebiet Redernswalde“ vom 3. Januar 2008 (GVBl.II/08, [Nr. 01], S.2)	Biodiversity conservation	Regulation	German	6
	Managementplan für das Gebiet Kölpinsee (2015), *Management Plan for Kölpinsee*	DE 2847-303 Kölpinsee	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet DE 2847-303 Kölpinsee	Biodiversity conservation	Natura 2000 Management Plan	German	193
	Managementplan für das Gebiet Kronhorst-Groß Fredenwalde (2015),*Management Plan for Kronhorst-Groß Fredenwalde*	DE 2848-303 Kronhorst-Groß Fredenwalde	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Kronhorst-Groß Fredenwalde	Biodiversity conservation	Natura 2000 Management Plan	German	233

Managementplan für das Gebiet Groß Ziehten (2015), *Management Plan for Groß Ziehten*	DE 3049-302 Groß Ziehten	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Groß Ziehten	Biodiversity conservation	Natura 2000 Management Plan	German	151
Managementplan für das Gebiet Melzower Forst (2015), *Management Plan for Melzower Forst*	DE 2849-302 Melzower Forst	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Melzower Forst	Biodiversity conservation	Natura 2000 Management Plan	German	273
Managementplan für das Gebiet Brodowin-Oderberg(2015), *Management Plan for Brodowin-Oderberg*	DE 3050-301 Brodowin -Oderberg	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Brodowin-Oderberg	Biodiversity conservation	Natura 2000 Management Plan	German	231
Managementplan für das Gebiet Arnimswalde (2015), *Management Plan for Arnimswalde*	DE 2848-301 Arnimswa lde	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Arnimswalde	Biodiversity conservation	Natura 2000 Management Plan	German	187
Managementplan für das Gebiet Suckower Haussee(2015), *Management Plan for Suckower Haussee*	DE 2848-301 Arnimswa lde	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Suckower Haussee	Biodiversity conservation	Natura 2000 Management Plan	German	91
Managementplan für das Gebiet Poratzer Moränenlandschaft (2015), *Management Plan Poratzer Moränenlandschaft*	DE 2948-304 Poratzer Moränenl andschaft	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Poratzer Moränenlandschaft	Biodiversity conservation	Natura 2000 Management Plan	German	301
Managementplan für das Gebiet Grumsiner Forst / Redernswalde (2015), *Management Plan for*	DE 2949-302 Grumsine r Forst /	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Grumsiner Forst / Redernswalde	Biodiversity conservation	Natura 2000 Management Plan	German	389

Grumsiner Forst/ Redernswalde	Redernswalde						
Managementplan für das Gebiet Kienhorst/Köllnsee/Eichheide(2015), *Management Plan for Kienhorst/Köllnsee/ Eichheide*	DE 3047-301 Kienhorst /Köllnsee/ Eichheide	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Kienhorst/Köllnsee/Eichheide	Biodiversity conservation	Natura 2000 Management Plan	German	227
Managementplan für das Gebiet Werbellinkanal (2015), *Management Plan forWerbellinkanal*	DE 3048-302 Werbellinkanal	Managementplanung Natura 2000 im Land Brandenburg - Managementplan für das Gebiet Werbellinkanal	Biodiversity conservation	Natura 2000 Management Plan	German	255
Waldgesetz des Landes Brandenburg (2004), *Brandenburg Forest Law*	LWaldG	Waldgesetz des Landes Brandenburg	Forestry	Law	German	19
Richtlinie zur Gewährung von Zuwendungen für Naturschutzmaßnahmen im Wald und Hilfsmaßnahmen zur Bewältigung der durch Extremwetterereignisse verursachten Folgen im Wald (2021), *Directive on Subsidies for Nature Protection Measures in Forests and Measures to address the Effects of Extreme Weather Events*	MLUK-Forst-RL-NSW und BEW	Richtlinie des Ministeriums für Landwirtschaft, Umwelt und Klimaschutz des Landes Brandenburg zur Gewährung von Zuwendungen für Naturschutzmaßnahmen im Wald und Hilfsmaßnahmen zur Bewältigung der durch Extremwetterereignisse verursachten Folgen im Wald	Forestry	Directive	German	15

	Waldbau-Richtlinie 2004 "Grüner Ordner" der Landesforstverwaltung Brandenburg (2004), *Silviculture Directive*		Waldbau-Richtlinie 2004 "Grüner Ordner" der Landesforstverwaltung Brandenburg	Forestry	Directive	German	143
	Entwicklungsprogramm für den ländlichen Raum Brandenburgs und Berlins 2014 – 2022 (2021), *Development Programme for Rural Areas of Brandenburg and Berlin 2014-2022*		Entwicklungsprogramm für den ländlichen Raum Brandenburgs und Berlins 2014 – 2022	Rural development	Development Plan	German	768
Thuringia	Thüringer Naturschutzgesetz (2019), *Thuringia Nature Protection Law*	ThürNatG	Thüringer Gesetz zur Ausführung des Bundesnaturschutzgesetzes und zur weiteren landesrechtlichen Regelung des Naturschutzes und der Landschaftspflege	Biodiversity conservation	Law	German	27
	Thüringer Gesetz über den Nationalpark Hainich (1997), *Thuringia Law on the National Park Hainich*	ThürNPHG	Thüringer Gesetz über den Nationalpark Hainich	Biodiversity conservation	Law	German	8
	Naturparkplan Eichsfeld-Hainich-Werratal: Band 2 Konzept (2015), *Nature Park Plan Eichsfeld-Hainich-Werratal Volume 2*		Naturparkplan Eichsfeld-Hainich-Werratal: Band 2 Konzept	Biodiversity conservation	Nature Park Plan	German	35
	Thüringer Grünes-Band-Gesetz (2018), *Thuringia Law on the Green Belt*	ThürGBG	Thüringer Gesetz über das Nationale Naturmonument "Grünes Band Thüringen"	Biodiversity conservation	Law	German	64

	Managementplan (Fachbeitrag Offenland) für das FFH-Gebiet 036 und SPA-Gebiet 14 „Hainich“ (DE 4828-301) (2018); *Management Plan for Hainich*	DE 4828-301 Hainich	Managementplan (Fachbeitrag Offenland) für das FFH-Gebiet 036 und SPA-Gebiet 14 „Hainich“ (DE 4828-301)	Biodiversity conservation	Natura 2000 Management Plan	German	161
	Managementplan (Fachbeitrag Offenland) für das FFH-Gebiet 020 „Ibenkuppe - Thomasbrücke - Östlicher Westerwald“ (DE 4727-320) und Teile des SPA 013 "Südliches Eichsfeld" (DE 4727-420) (2017), *Management Plan for Ibenkuppe - Thomasbrücke - Östlicher Westerwald and SPA Südliches Eichsfeld*	DE 4727-320 Ibenkuppe - Thomasbrücke - Östlicher Westerwald and SPA DE 4727-420 Südliches Eichsfeld	Managementplan (Fachbeitrag Offenland) für das FFH-Gebiet 020 „Ibenkuppe - Thomasbrücke - Östlicher Westerwald“ (DE 4727-320) und Teile des SPA 013 "Südliches Eichsfeld" (DE 4727-420)	Biodiversity conservation	Natura 2000 Management Plan	German	299
	Naturerbe-Entwicklungsplan für die Naturerbefläche des Bundes „Dörna“ mit Ergänzungen für einen Managementplan-Fachbeitrag Offenland für das FFH-Gebiet Nr. (Thüringen) 22 „Dörnaer Platz“ (2019), *Natural Heritage Development Plan for the Federal*	DE 4728-301 Dörna	Naturerbe-Entwicklungsplan für die Naturerbefläche des Bundes „Dörna“ mit Ergänzungen für einen Managementplan-Fachbeitrag Offenland für das FFH-Gebiet Nr. (Thüringen) 22 „Dörnaer Platz“	Biodiversity conservation	Natura 2000 Management Plan	German	273

	Natural Heritage Site Dörna with additions for a Management Plan for Dörnaer Platz						
	Förderung von Vorhaben zur Entwicklung von Natur und Landschaft (ENL) (2015), *Regulation on Funding for the Development of Nature and Landscape*	ENL	Förderung von Vorhaben zur Entwicklung von Natur und Landschaft (ENL) Richtlinie des Thüringer Ministeriums für Umwelt, Energie und Naturschutz (TMUEN) vom 16.11.2015, geändert am 29.11.2018	Biodiversity conservation	Regulation	German	10
	Verordnung zur Festsetzung von Europäischen Vogelschutzgebieten, Schutzobjekten und Erhaltungszielen (2008), *Regulation on the Determination of European Specially Protected Areas*	ThürNat2000-ErhZVO	Verordnung zur Festsetzung von Europäischen Vogelschutzgebieten, Schutzobjekten und Erhaltungszielen	Biodiversity conservation	Regulation	German	537
	Thüringer Waldgesetz (2008), *Thuringia Forest Law*	ThürWaldG	Thüringer Waldgesetz	Forestry	Law	German	24
	Thüringer Richtlinie zur Förderung forstwirtschaftlicher Maßnahmen (2014), *Thuringia Directive on Forestry Measures*		Thüringer Ministerium für Infrastruktur und Landwirtschaft (TMIL) Thüringer Richtlinie zur Förderung forstwirtschaftlicher Maßnahmen	Forestry	Regulation	German	39

	Dienstordnung Waldbau - 2.8 Anweisungen zum Waldbau im Staatswald der Landesforstanstalt (2015), *Service Regulation Silviculture for State Forests*		Dienstordnung Waldbau - 2.8 Anweisungen zum Waldbau im Staatswald der Landesforstanstalt	Forestry	Regulation	German	36
	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Ibenkuppe - Thomasbrücke - Östlicher Westerwald“ EU-Nr. DE 4727-320, [TH-Nr. 020] und einer Teilfläche vom EG-Vogelschutzgebiet „Südliches Eichsfeld“ EU-Nr. DE 4727-420, [TH-Nr. 13] (2017), *Technical Contribution Forests for the Natura 2000 Management Plan for Ibenkuppe - Thomasbrücke - Östlicher Westerwald and SPA Südliches Eichsfeld*	Forest Contribution on FFH DE 4727-320 and SPA DE 4727-420	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Ibenkuppe - Thomasbrücke - Östlicher Westerwald“ EU-Nr. DE 4727-320, [TH-Nr. 020] und einer Teilfläche vom EG-Vogelschutzgebiet „Südliches Eichsfeld“ EU-Nr. DE 4727-420, [TH-Nr. 13]	Forestry	Natura 2000 Management Plan	German	35
	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Muschelkalkhänge von Großbartloff bis Faulungen“ EU-Nr. DE 4727-301 [TH-Nr. 021] und einer Teilfläche vom	Forest Contribution on FFH DE 4727-301 and SPA DE 4727-420	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Muschelkalkhänge von Großbartloff bis Faulungen“ EU-Nr. DE 4727-301 [TH-Nr. 021] und einer Teilfläche vom EG-Vogelschutzgebiet „Südliches	Forestry	Natura 2000 Management Plan	German	32

	EG-Vogelschutzgebiet „Südliches Eichsfeld“ EU-Nr. DE 4727-420 [TH-Nr. 013] (2014), *Technical Contribution Forests for the Natura 2000 Management Plan for Muschelkalkhänge von Großbartloff bis Faulungen and SPA Südliches Eichsfeld*		Eichsfeld“ EU-Nr. DE 4727-420 [TH-Nr. 013]				
	Fachbeitrag Wald zum Managementplan für das Natura 2000-Gebiet FFH-Gebiet „Dörnaer Platz“ EU-Nr. DE 4728-301, [TH-Nr. 022] (2012), Technical Contribution Forests *for* the Natura 2000 Management Plan for Dörnaer Platz	Forest Contribution on FFH DE 4728-301	Fachbeitrag Wald zum Managementplan für das Natura 2000-Gebiet FFH-Gebiet „Dörnaer Platz“ EU-Nr. DE 4728-301, [TH-Nr. 022]	Forestry	Natura 2000 Management Plan	German	23
	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Hainich“ EU-Nr. DE 4828-301, [TH-Nr. 036] und EG-Vogelschutzgebiet „Hainich“ EU-Nr. DE 4828-301, [TH-Nr. 14] - Planungsgebiet 036 (2018), Technical Contribution Forests *for* the Natura 2000	Forest Contribution on DE 4828-301 and SPA DE 4828-301	Fachbeitrag Wald zum Managementplan für die Natura 2000-Gebiete FFH-Gebiet „Hainich“ EU-Nr. DE 4828-301, [TH-Nr. 036] und EG-Vogelschutzgebiet „Hainich“ EU-Nr. DE 4828-301, [TH-Nr. 14] - Planungsgebiet 036 (2018), Technical	Forestry	Natura 2000 Management Plan	German	42

	Management Plan for Hainich and SPA Hainich						
Baden-Württemberg	Gesetz des Landes Baden-Württemberg zum Schutz der Natur und zur Pflege der Landschaft (2015), *Baden-Württemberg Nature Protection and Landscape Maintenance Law*	BWNatSchG	Gesetz des Landes Baden-Württemberg zum Schutz der Natur und zur Pflege der Landschaft	Biodiversity conservation	Law	German	46
	Verordnung über das Biosphärengebiet Schwäbische Alb (2008), *Regulation on the Biosphere Reserve Schwäbische-Alb*		Verordnung des Ministeriums für Ernährung und Ländlichen Raum über das Biosphärengebiet Schwäbische Alb	Biodiversity conservation	Regulation	German	11
	Verwaltungsvorschrift zur Förderung und Entwicklung des Naturschutzes, der Landschaftspflege und Landeskultur (2015), *Regulation on Funding for Nature Conservation, Land Maintenance and Regional Culture*	LPR	Verwaltungsvorschrift des Ministeriums für Umwelt, Klima und Energiewirtschaft Baden-Württemberg zur Förderung und Entwicklung des Naturschutzes, der Landschaftspflege und Landeskultur (Landschaftspflegerichtlinie)	Biodiversity conservation	Regulation	German	49

	Das Rahmenkonzept Band 1: Unser Gebiet Ausgangssituation, Herausforderungen und Entwicklungspotenziale (Biosphärengebiet Schwäbische-Alb) (2012), *Framework Concept Volume 1: Our Area (Biosphere Reserve Schwäbische-Alb)*		Das Rahmenkonzept Band 1: Unser Gebiet Ausgangssituation, Herausforderungen und Entwicklungspotenziale (Biosphärengebiet Schwäbische-Alb)	Biodiversity conservation	Framework Concept	German	62
	Das Rahmenkonzept Band 2: Unsere Strategie Leitbilder, Entwicklungsziele, Leitprojekte (Biosphärengebiet Schwäbische-Alb) (2012), *Framework Concept Volume 2: Our Strategy (Biosphere Reserve Schwäbische-Alb)*		Das Rahmenkonzept Band 2: Unsere Strategie Leitbilder, Entwicklungsziele, Leitprojekte (Biosphärengebiet Schwäbische-Alb)	Biodiversity conservation	Framework Concept	German	134
	Das Rahmenkonzept Band 3: Unser Weg Leitprojekte, Projekte und Projektideen (Biosphärengebiet Schwäbische-Alb) (2012), *Framework Concept Volume 3: Our Way (Biosphere Reserve Schwäbische-Alb)*		Das Rahmenkonzept Band 3: Unser Weg Leitprojekte, Projekte und Projektideen (Biosphärengebiet Schwäbische-Alb)	Biodiversity conservation	Framework Concept	German	172
	Managementplan für das FFH-Gebiet 7521-341 Albtrauf Pfullingen	DE 7521-341	Managementplan für das FFH-Gebiet 7521-341 Albtrauf Pfullingen	Biodiversity conservation	Natura 2000 Management Plan	German	191

(2019), *Management Plan for Albtrauf Pfullingen*						
Managementplan für das FFH-Gebiet 7522-341 Uracher Talspinne (2017), *Management Plan for Uracher Talspinne*	DE 7522-341	Managementplan für das FFH-Gebiet 7522-341 Uracher Talspinne	Biodiversity conservation	Natura 2000 Management Plan	German	216
Managementplan für das FFH-Gebiet 7622-341 Großes Lautertal (2020), *Management Plan for Großes Lautertal*	DE 7622-341	Managementplan für das FFH-Gebiet 7622-341 Großes Lautertal	Biodiversity conservation	Natura 2000 Management Plan	German	225
Verwaltungsvorschrift über die Gewährung von Zuwendungen für Nachhaltige Waldwirtschaft (2020), *Regulation on Subsidies for Sustainable Forestry*	VwV NWW	Verwaltungsvorschrift des Ministeriums für Ländlichen Raum und Verbraucherschutz über die Gewährung von Zuwendungen für Nachhaltige Waldwirtschaft	Forestry	Regulation	German	128
Baden-Württemberg Landeswaldgesetz - Reform 2019 (2019), *Baden-Württemberg State Forest Law*	BW LWaldG	Waldgesetz für Baden-Württemberg (Landeswaldgesetz - LWaldG) in der Fassung vom 31. August 1995 geändert durch VRG vom 1 .Juli 2004 und Gesetz vom 13. Dezember 2005	Forestry	Law	German	43
Richtlinie Landesweiter Waldentwicklungstypen (2014), *Directive on State-wide Forest Development Types*		Richtlinie Landesweiter Waldentwicklungstypen	Forestry	Directive	German	118

	Germany - Rural Development Programme (Regional) - Baden-Württemberg (2014)	Germany - Rural Development Programme (Regional) - Baden-Württemberg	Rural Developement	Programme	English/ German	1051
Hainich	Nationalparkplan für den National Park Hainich (2007, *National Park Plan for the National Park Hainich*	Nationalparkplan für den National Park Hainich	Biodiversity conservation	National Park Plan	German	117

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Appendix E. Metadata sheet for the policy document analysis on the governance of anthropogenic capitals in the co-production of nature's contributions to people in forests. Based on Isaac et al. (2022) S4.

Category	*Code*	*Description*	*Definition (if applicable)*	*Selection*
1) general policy document info	policy document ID	identification number of the document		number (continuous)
	coder	person coding the policy document		RI, LD, JH, JK, BML
	institution	name of institution that has published the document		text
	governance level	governance level at which this institution operates		European Union; Germany; Brandenburg; Thuringia; Baden-Württemberg; Schorfheide; Hainich; Schwäbische-Alb
	year	policy document publication year		text
	title	policy document title		text
	policy document type	type of policy document		law; directive; regulation; strategy; biosphere reserve plan; natura 2000 management plan; other
2) temporal scale	temporal scale	years the policy document has been in action		text
3) spatial scale	spatial scale	spatial scale the policy document addresses		European Union; Germany; Brandenburg; Thuringia; Baden-Württemberg; Schorfheide; Hainich; Schwäbische-Alb
4) policy field	policy field	which policy field does the policy document address		forestry; biodiversity conservation; energy; climate; rural development; agriculture; other

5) NCP co-production general	explicit co-production	policy document uses the concept of NCP co-production explicitly		0= no; 1= yes
	implicit co-production	policy document uses the concept of co-production implicitly		0= no; 1= yes
	polycentric governance	policy document addresses several governance levels	*"Polycentric*: connotes multiple centres of decision-making authority which are de jure independent or de facto autonomous of each other. *Polycentric Governance*: governance that has polycentric attributes, where governance is a process by which the repertoire of rules, norms, and strategies that guide behaviour within a given realm of policy interactions are formed, applied, interpreted, and reformed." (Stephan et al., 2019, p.40)	0= no; 1= yes
	comments	other remarks or comments		text
6) NCP group	NCP group	category to which the co-produced NCP belongs		material; regulating; non-material

	focal forest NCP	sub-category to which the NCP belongs to in case that it is a material (defined in previous column) (see sub-categories on the right)		timber production; food; habitat creation and maintenance; other physical or psychological experiences; bird watching; cultural experiences through plants; regulation of climate; regulation of detrimental organisms; regulation of hazards and extreme events; soil formation and protection; other NCP
	NCP (in words)	describe NCP in words		text
7) capital types	natural capital description	describe the natural capital underpinning the NCP in words	Natural capital comprises the stock of natural resources and ecosystem functions that independently or combined with anthropogenic capitals provide NCP (Goodwin, 2003; Palomo et al., 2016).	text
	human capital category	category to which human capital belongs to (if applicable)	Human capital refers to people's capabilities including health, informal knowledge, formal knowledge, skills, motivation, and labour that can yield a flow of NCP (Goodwin, 2003; Palomo et al., 2016).	labour; knowledge; skills; other HC
	human capital description	describe human capital indicator in words		text

	social capital category	category to which social capital belongs to (if applicable)	Social capital includes all intangible assets associated with interactions between people including formal and informal networks, trust, and formal and informal institutions required for enhancing the flow of NCP. (Palomo et al., 2016)	networks; informal institutions; other SC
	social capital description	describe social capital indicator in words		text
	physical capital category	category to which physical capital belongs to (if applicable)	Physical capital refers to technological or manufactured assets that contribute to the flow of NCP (Goodwin, 2003; Palomo et al., 2016; Pretty, 2003).	tools and machinery; infrastructure and built capital; other PC
	physical capital description	describe physical capital indicator in words		text
	financial capital	if co-production involves financial capital	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 that contribute to the flow of NCP. (Palomo et al., 2016)	direct payments; subsidies; other FC

	financial capital description	describe financial capital indicator in words		text
	prohibited actions	actions prohibited by policy in relation to NCP		text
8) general info on governance	governance level	level at which governance is executed	"At the level of governance, the delivery of ecosystem services is arbitrated by the suite of institutions in place, such as land tenure, communal rules and norms, and taxes and subsidies" (Malinga et al., 2018, p. 8).	European Union; Germany; Brandenburg; Thuringia; Baden-Württemberg; Schorfheide; Hainich; Schwäbische-Alb
	governance level description	describe governance level indicator in words		text
	governance affecting capitals	whether governance affects capitals		human capital; social capital; physical capital; financial capital; multiple
	governance affecting NCP	whether governance affects NCP		material; regulating; non-material
	formal governance	governance with involvement of formal institutions and formal rules	"formally sanctioned rules such as laws, property rights, and bureaucratic functions of government" (Gómez-Baggethun et al., 2013, p. 1212).	0= no; 1= yes
	formal governance description	describe formal governance indicator in words		text

	informal governance	governance with involvement of informal institutions e.g., traditions or customary right, informal groups	"communal lands, nonformal institutions such as traditions and customary right, established on the basis of local and traditional ecological knowledge" (Gómez-Baggethun et al., 2013, p. 1212)	0= no; 1= yes
	informal governance description	describe informal governance indicator in words		text
9) governance modes	hierarchical governance	Top-down formal governance steering lower entities	Hierarchical governance concerns regulations that influence NCP as well as the other modes of governance (Primmer et al., 2015). In contrast to collaborative governance, hierarchical governance is executed by state actors through formal institutions. Formal institutions exist mainly in the form of policies (e.g., frameworks, laws, regulations) that directly affect NCP or the other governance modes. As interdependencies between policies across governance levels exist, hierarchical governance is often studied in multi-level contexts. Governance of NCP is therefore often linked to scale mismatches (Borgström et al., 2006; Winkler et al., 2021). Scale mismatches occur when ecosystem boundaries do not match with the borders of administrative units. A positive	0= no; 1= yes

		example is the Water Framework Directive, which was the first European Union directive using a natural unit (water catchments) for governance, rather than administrative units such as counties (Moss, 2012).	
hierarchical governance description	describe hierarchical governance indicator in words		text
scientific technical governance	governance based on scientific arguments or involving consultation of scientists at the science policy interface	Scientific-technical governance refers to the processes of decision making based on scientific and technical arguments (Primmer et al., 2015). Experts who are not necessarily scientists influence decisions play a vital role in this process. The underlying expectation for scientific-technical governance is that effective dissemination of scientific knowledge leads to better governance (Huth and Possingham, 2011; Sutherland et al., 2004). Land-use planning serves as an example for this governance mode as it incorporates scientific arguments when making decisions about potential trade-offs between NCP (Paavola and Hubacek, 2013).	0= no; 1= yes

	scientific technical governance description	describe scientific-technical governance indicator in words		text
	collaborative governance	bottom-up based governance seeking to overcome conflicts through stakeholder inclusion in participatory processes	Collaborative governance stresses the importance of collective learning and bottom-up participatory processes that embrace diverse stakeholder perspectives (Primmer et al., 2015). Moreover, collaborative governance is best executed when based open and transparent processes to collective problem-solving (Newig and Fritsch, 2009). Participatory processes are often considered to contribute positively to ecological outcomes (Bäckstrand et al., 2010).	0= no; 1= yes
	collaborative governance description	describe collaborative governance indicator in words		text
	adaptive governance	governance based on the learning about ever changing circumstances	Adaptive responds to changes in the social or ecological system and is often organised polycentrically by involving various decision-making centres (Folke et al., 2005). It is used to increase the responsive capacity to changing circumstances, including changing societal values (Burkhard et al., 2012). Examples are stewardship approaches to	0= no; 1= yes

		ecosystems (Chapin III et al., 2015; Olsson et al., 2008), or approaches that promote local learning (Cork et al., 2006).	
adaptive governance description	describe adaptive governance indicator in words		text
governing strategic behaviour	strategic planning of actions against certain forms of policies or governance	Governing of strategic behaviour features the potential of governance arrangements and the interactions between them to be transformative (Primmer et al., 2015). It refers to market-based or commercial approaches. This implies the aim to influence policy-making processes through lobbying with the goal of affecting policies and protecting certain interests (Newig and Fritsch, 2009; Primmer et al., 2015). Besides, governing of strategic behaviour can nudge behaviour in a wanted direction (Primmer, 2011). Payments for ecosystem services are a common example of governing of strategic behaviour often referred to in the literature (see e.g., Börner et al., 2010; Rival, 2010; Van Hecken and Bastiaensen, 2010).	0= no; 1= yes
governing strategic behaviour description	describe governing of strategic behaviour indicator in words		text

	other forms of governance	other forms of governance not included above	open
	general comments	general comments about the publication	open
10) general comments			

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Appendix F. Exemplary verbatims of nature's contributions to people in German and English

Nature's contributions to peoples		*Exemplary Verbatims (English translation)*	*Original verbatim*	*Policy*	*Page*
Material	Timber production	*The goal of timber production, which occurs every 5 years, is ongoing forest management:* *Harvest of valuable, harvestable trees according to quality and a defined diameter,* • *Removal of damaged or dependent trees* • *Selection and raising* • *Mixed regulation to achieve shares in tree selection* • *Supporting tree offspring*	Die Zielsetzung der Holznutzung, die i.d.R. in einem Intervall von 5 Jahren erfolgt, ist in der Dauerwaldbewirtschaftung: Ernte wertvoller, hiebsreifer Bäume nach Qualität und Zieldurchmesser Entnahme von beschädigten und abgängigen Bäumen Auslese und Erziehung Mischungsregulierung zur Erreichung angestrebter Baumartenanteile Förderung des Nachwuchses	Directive on State-wide Forest Development Types Baden-Württemberg (2014)	4-5
	Food	*The restrictions in §44 paragraph 1 number 4 and paragraph 2 sentence 1 number 1 of the Federal Nature Conservation Law do not apply to the following mushroom species, if they are collected in small amounts in nature for personal use (...)*	Die Verbote des § 44 Absatz 1 Nummer 4 und Absatz 2 Satz 1 Nummer 1 des Bundesnaturschutzgesetzes gelten nicht für Pilze der nachstehend aufgeführten Arten, soweit sie in geringen Mengen für den eigenen Bedarf der Natur entnommen werden (…)	Federal Species Protection Regulation (2005)	§2.1

Non-material	Birdwatching	*Conservation of existing spatial patterns and tree composition in stock, which are within the inner protection zone (100-m-radius and close to eyries of specially protected bird species, in particular in combination with measures to support rejuvenation, should only allow extraction of trees in single logs and outside the mating and breeding seasons of birds, as this is relevant for the following species* • *Red kite,* • *Black stork,* • *and Eagle owl (…).*	Erhaltung der bestehenden Raumstruktur und Baumartenzusammensetzung von Beständen, die laut Positivliste zur inneren Schutzzone (100-m-Umkreis) bei Horsten besonders geschützter Vogelarten gehören, insbesondere im Zusammenhang mit Maßnahmen zur Verjüngungsnutzung, eine Entnahme von Bäumen sollte hier ausschließlich einzelstammweise und außerhalb der Balz-, Brut- und Aufzuchtzeiten erfolgen, da dies für die Arten - Rotmilan, - Schwarzstorch und - Uhu von besonderer Bedeutung ist, (…).	Technical Contribution Forests on the Natura 2000 Management Plan for Ibenkuppe - Thomasbrücke - Östlicher Westerwald and SPA Südliches Eichsfeld (2017)	21

Cultural experiences through plants	*Nature conservation areas are legally binding areas, in which nature and landscape are especially protected in their entireness and in their singular parts, where it is needed for* *1. preserving, developing, or regenerating habitats, biotopes, communities of specific wild animal and plant species,* *2. scientific, natural history, or geographic reasons,* *3. or due to their rarity, specific characteristic, or outstanding beauty.*	Naturschutzgebiete sind rechtsverbindlich festgesetzte Gebiete, in denen ein besonderer Schutz von Natur und Landschaft in ihrer Ganzheit oder in einzelnen Teilen erforderlich ist 1. zur Erhaltung, Entwicklung oder Wiederherstellung von Lebensstätten, Biotopen oder Lebensgemeinschaften bestimmter wild lebender Tier- und Pflanzenarten, 2. aus wissenschaftlichen, naturgeschichtlichen oder landeskundlichen Gründen oder 3. wegen ihrer Seltenheit, besonderen Eigenart oder hervorragenden Schönheit.	Federal Nature Conservation and Maintenance Law (2009)	§23.1
Other physical or psychological experiences	*Forests play an important role for physical and psychological regeneration of people and are intensively used for recreation, leisure activities, and sports, particularly in conurbation and outer conurbation areas.*	Insbesondere in Ballungs- und Ballungsrandgebieten hat der Wald eine wichtige Rolle für die physische und psychische Regeneration des Menschen und wird für Erholung, Freizeit und Sport intensiv genutzt.	German Forest Strategy 2020 (2011)	29

Regulating	Habitat creation and maintenance	*(...) Protection of existing and formally protected forest biotopes in their current spatial coverage, characteristic condition, and as habitat for the occurring biotope specific species in fauna and flora (is important), (...)*	(…) Erhaltung der vorkommenden gesetzlich geschützten Waldbiotope in ihrem derzeitigen flächenmäßigen Umfang und in ihrem jeweils charakteristischen Zustand sowie als Lebensstätte der hier vorkommenden biotoptypischen Tier- und Pflanzenarten (ist wichtig), (…)	Technical Contribution Forests on the Natura 2000 Management Plan for Muschelkalkhänge von Großbartloff bis Faulungen and SPA Südliches Eichsfeld (2014)	16
	Regulation of climate	*Forests and the forestry sector are impacted by climate change but contribute to climate mitigation simultaneously. (...) Adapting forests to climate change can be done by selecting suitable tree species and trees from origins that show respective climate variabilities.*	Wald und Forstwirtschaft sind dem Klimawandel ausgesetzt, tragen auf der anderen Seite aber auch aktiv zum Klimaschutz bei. (…) Die Anpassung der Wälder an den Klimawandel kann über geeignete Baumartenwahl und Herkünfte mit entsprechender Klimavariabilät erfolgen.	German Forest Strategy 2020 (2011)	22-23
	Regulation of detrimental organisms	*Funding can be sought for (...) tackling detrimental organisms by finding and processing infested or potentially infested timber (e.g., by cleaning cuts, debarking, bark disposal, moving and transport of timber) or other measures that reduce the timber's suitability for breeding and thereby minimise or diminish potential further risks arising.*	Förderfähig sind (…) die Bekämpfung von Schadorganismen durch Auffinden und Aufarbeitung von befallenem oder unmittelbar befallsgefährdetem Holz (z.B. Sanitärhiebe, Entrinden, Rinde entsorgen, Rücken und Transport von Holz) oder sonstige Maßnahmen, die die Bruttauglichkeit von Holz, Restholz, Reisig soweit herabsetzen, dass Gefährdungen von diesem Material nicht mehr ausgehen oder gar nicht erst entstehen (…)	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	110

	Regulation of hazards and extreme events	*Measures need be in immediate relation to coping with damages due to extreme weather and the results of these (e.g., bark beetle) and the restoration of location specific and climate adaptive forests on the damaged areas.*	Die Maßnahmen müssen unmittelbar in Zusammenhang stehen mit der Bewältigung der durch Extremwetterereignisse bedingten Schäden und Folgeschäden (z. B. Borkenkäfer) sowie der Wiederherstellung standortgerechter und klimaangepasster Waldbestände auf den geschädigten Flächen dienen.	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	110
	Soil formation and protection	*The regeneration and protection of natural soil functions is essential to sustainable, careful,and proper forest management.*	Zur nachhaltigen, pfleglichen und sachgemäßen Bewirtschaftung des Waldes gehört insbesondere die natürlichen Bodenfunktionen wiederherzustellen und zu erhalten.	Brandenburg Forest Law (2004)	§4.3

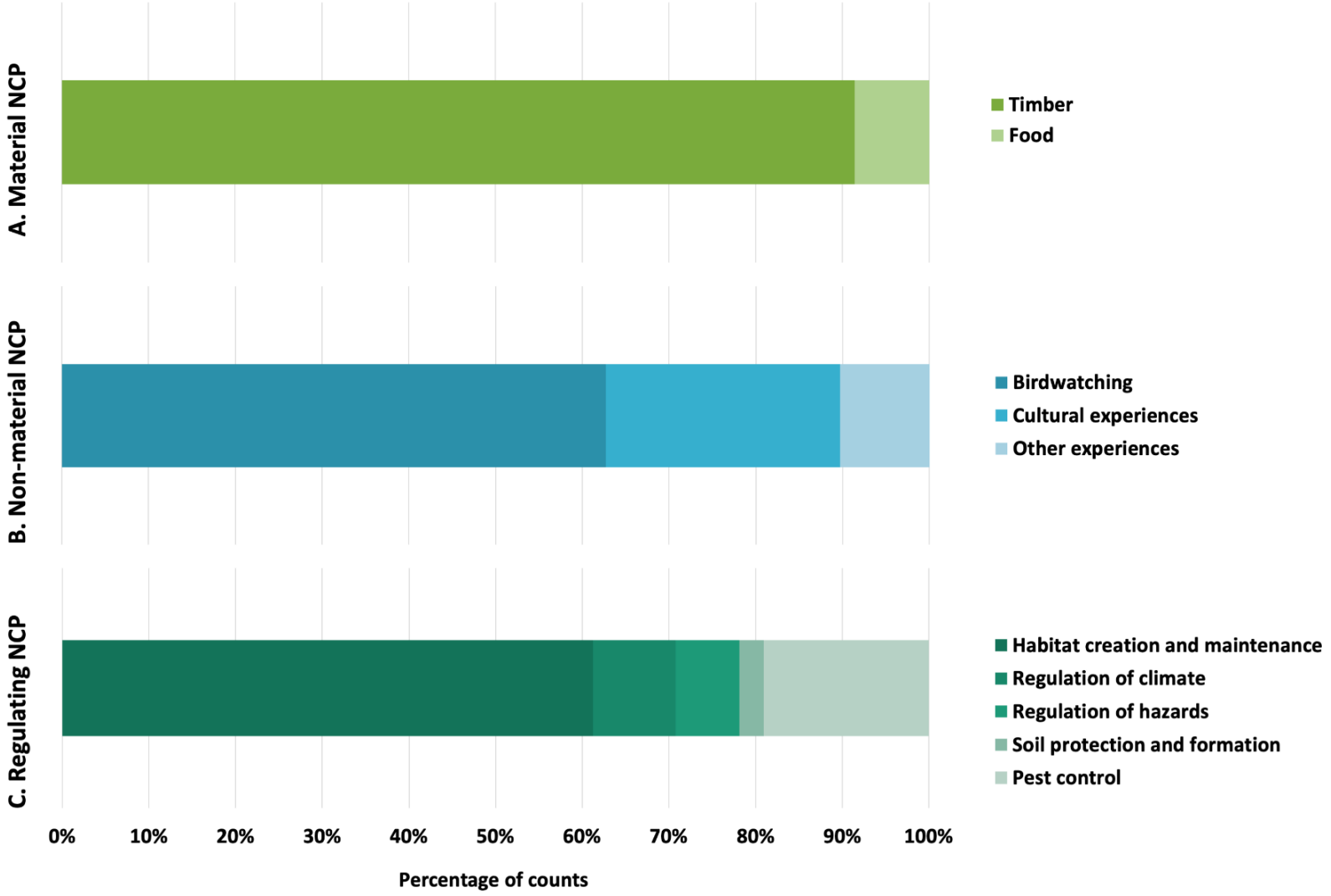
Appendix G. Exemplary verbatims of anthropogenic capitals in German and English

Anthropogenic capitals		*Exemplary Verbatims (English translation)*	*Original verbatim*	*Policy*	*Page*
Human capital	Labour	Trees with the highest potential are to be specifically supported by targeted thinning and removal of oppressors.	Die bestveranlagten herrschenden Bäume sind gezielt durch positive Auslesedurchforstung und durch Entnahme von Bedrängern zu fördern.	Silviculture Directive Brandenburg (2004)	8
	Knowledge	*To ensure the sustainable development of rural areas, it is necessary to focus on a limited number of core priorities relating to knowledge transfer and innovation in agriculture, forestry, and rural areas, (...) the sustainable management of forests, (...)*	To ensure the sustainable development of rural areas, it is necessary to focus on a limited number of core priorities relating to knowledge transfer and innovation in agriculture, forestry and rural areas, (…) the sustainable management of forests, (…)	EAFRD Funding Regulation (2013)	Article 1.4
	Skills	*By including silvicultural programmes, this directive provides the tools to enable forest owners to achieve their operational goals related to silviculture.*	Die Richtlinie liefert mit ihren waldbaulichen Behandlungsprogrammen das Handwerkszeug, das die Waldbesitzer in die Lage versetzt, ihre betrieblichen Ziele in puncto Waldentwicklung zu erreichen.	Directive on state-wide Forest Development Types Baden-Württemberg (2014)	3

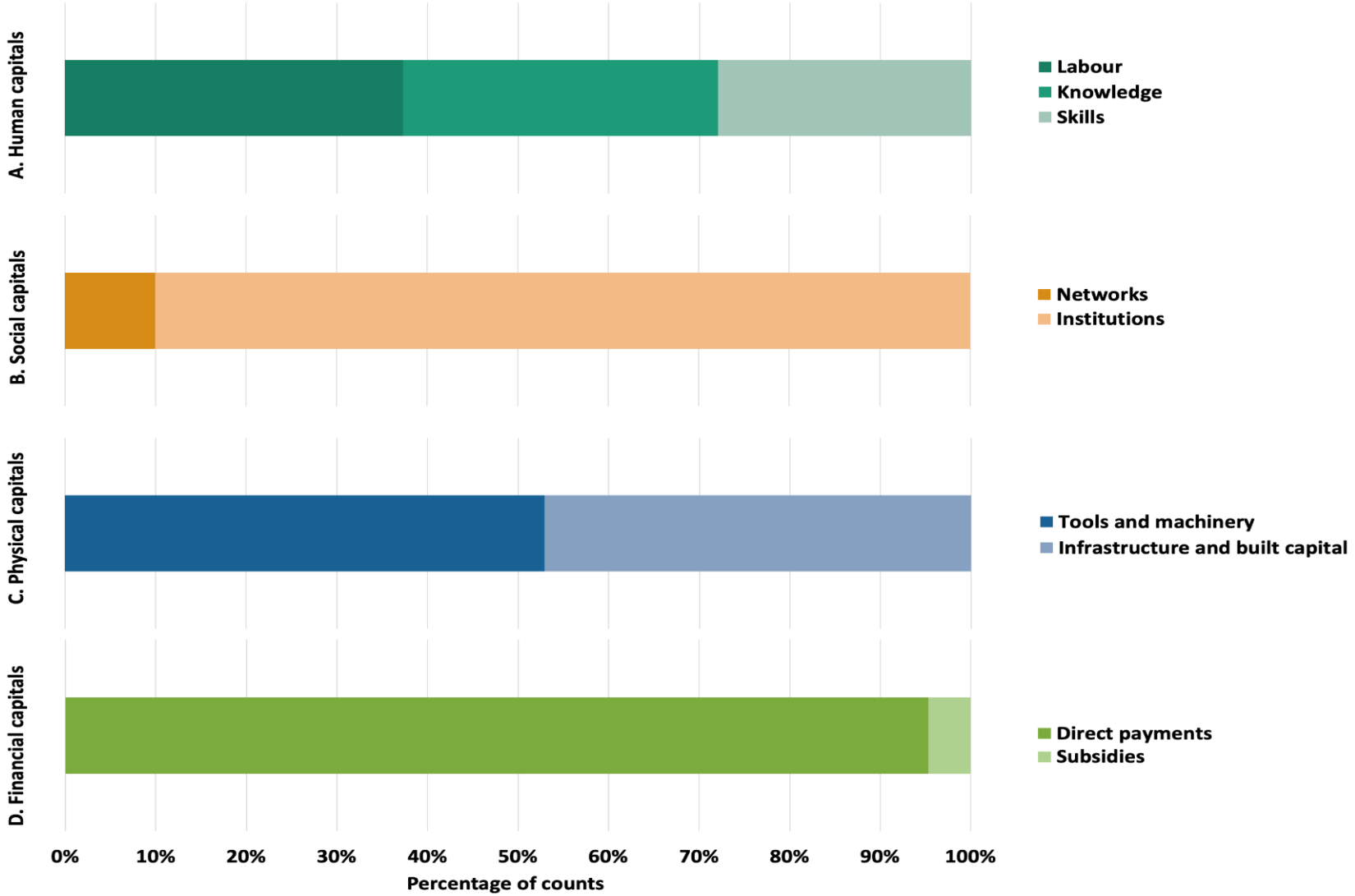
Social capital	Networks	*Forest management associations are associations of landowners under private law that aim to improve the management of the attached forest areas and those areas dedicated to afforestation, and overcome disadvantages related to small-sized forests, disadvantaged areas, fragmentation of ownership, general hotch-potch, insufficient forest openings, or other structural disadvantages.*	Forstbetriebsgemeinschaften sind privatrechtliche Zusammenschlüsse von Grundbesitzern, die den Zweck verfolgen, die Bewirtschaftung der angeschlossenen Waldflächen und der zur Aufforstung bestimmten Grundstücke (Grundstücke) zu verbessern, insbesondere die Nachteile geringer Flächengröße, ungünstiger Flächengestalt, der Besitzzersplitterung, der Gemengelage, des unzureichenden Waldaufschlusses oder anderer Strukturmängel zu überwinden.	Federal Forest Law (1975)	§16
	Institutions	*Based on their competence, federal and state government agencies must support the implementation of nature conservation goals and landscape maintenance.*	Die Behörden des Bundes und der Länder haben im Rahmen ihrer Zuständigkeit die Verwirklichung der Ziele des Naturschutzes und der Landschaftspflege zu unterstützen.	Federal Nature Conservation and Maintenance Law (2009)	§2.2
Physical capital	Tools and machinery	*Use should be performed moderately for the soil and in deep frost. Timber should be moved by horse instead of establishing skid trails.*	Die Nutzung sollte bodenschonend, vor allem bei tiefem Frost, stattfinden. Auf Anlage eines Rückegassen-Systems sollte möglichst verzichtet werden und stattdessen mit Pferden gerückt werden.	Management Plan Poratzer Moränenlandschaft (2015)	217
	Infrastructure and built capital	*Forest roads serve forest development for the purposes of forest management and recreation of visitors.*	Waldwege dienen der Erschließung des Waldes zum Zwecke seiner Bewirtschaftung und der Erholung der Waldbesucher.	Baden-Württemberg State Forest Law (2019)	§19.1
Financial capital	Direct payments	*The payments cover 80% of proven spendings at max. according to number 3.2.1. Payments can cover up to 90% of proven spendings in case of small private landowners (under 20ha forest ownership).*	Die Höhe der Zuwendung beträgt für Maßnahmen nach Nr. 3.2.1 bis zu 80 % der nachgewiesenen Ausgaben. Im Fall von Kleinprivatwaldbesitzern (unter 20 ha Waldbesitz) kann die Höhe der Zuwendung bis zu 90 % der nachgewiesenen Ausgaben betragen.	Masterplan for the Joint Efforts for Improvements in Agricultural Structure and Coastal Protection 2021-2024 (2020)	113

	Subsidies	*The forestry sector is to be financially supported by the state for the productive, protective, and social function of forests according to §1.*	Die Forstwirtschaft soll wegen der Nutz-, Schutz- und Erholungsfunktionen des Waldes nach § 1 öffentlich gefördert werden.	Federal Forest Law (1975)	§41.1

Appendix H. Data on the specific numbers for each co-produced forest NCP found in the policy documents.



Appendix I. Data on the specific numbers for each anthropogenic capital found in the policy documents.



Appendix J. Counts of mentions of anthropogenic capitals contributing nature's contributions to people in forests. Data for Fig. 5 Heatmap.

	Human capital			*Social capital*	*Physical capital*		*Financial capital*
Nature's contributions to people	*Labour*	*Knowledge*	*Skills*	*Institutions*	*Tools and machinery*	*Infrastructure and built capital*	*Direct payments*
Timber production	57	49	57	111	31	26	46
Birdwatching	20	18	7	20	5	1	6
Cultural experiences through plants	8	12	7	20	2	0	4
Habitat creation and maintenance	32	23	28	73	5	11	43
Regulation of detrimental organisms	13	13	3	25	10	4	17

Appendix K. X^2 statistics representing the associations between governance levels and NCP categories, anthropogenic capitals, and modes of governance based on contingency tables. * Significant associations at $P<0.05$; ** and at $P<0.01$; (+) positive and (-) negative significant associations are indicated.

	European Union	*Germany*	*Federal States*	*Local*
NCP categories				
Material	0.332	0.193	0.511	(-) 1.470*
Non-material	(-) 1.731*	(-) 6.345*	(-) 0.230*	(+) 14.301**
Regulating	5.412	(+) 12.784**	2.299	(-) 37.218**
Anthropogenic capitals				
Human	(+) 6.916**	2.830	2.671	1.011
Social	0.666	3.283	2.251	(-) 5.574*
Physical	2.500	1.922	(-) 4.104*	(+) 4.254*
Financial	0.182	(+) 6.553*	(+) 35.740**	(-) 68.584**
Governance modes				
Hierarchical	3.284	2.876	(+) 23.262**	(+) 7.777**
Scientific-Technical	1.750	0.034	0.084	0.892
Collaborative	0.020	2.053	0.288	2.197
Adaptive	0.681	1.741	1.483	(-) 7.163**
Strategic behaviour	(+) 13.349**	(+) 36.827**	0.859	(-) 29.323**

Appendix 5: Supplementary material for Isaac et al. (in preparation) The forest beyond the trees: a network perspective on governing nature's contributions to people co-production (Chapter IV).

Supplementary material for Isaac et al. *The forest beyond the trees: a network perspective on governing nature's contributions to people co-production*

Disclaimer: This supplementary material has not been peer-reviewed.

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Appendix

S1 Table. Defining anthropogenic capitals that underpin nature's contributions to people co-production. Adapted from Isaac et al., (2022) based on Palomo et al. (2016).

Type of anthropogenic capital	*Definition*	*Forest related examples*
Human capital	Includes people's capabilities such as health, knowledge, skills, motivation, and labour that contribute to the provision of NCP.	Forest management, forestry specific knowledge, habitat specific knowledge.
Social capital	Any form of interaction between people through networks or trust as well as within or between institutions that supports the provision of NCP. Formal institutions, such as conservation agencies, that regulate the use and management of NCP or NCP supply.	Forestry associations that organise forest management and timber harvest. European directives, national laws or informal rules related to forest management. International certification schemes of forest-derived products.
Physical capital	Manufactured or technological capitals that are used to provide NCP. Infrastructure and built capital that is used to access NCP.	Machinery and tools used in forestry such as chainsaws, harvesters, trucks, or fences. Logging roads or footpaths.
Financial capital	Any form of financial stream in the form of savings, credits, subsidies, direct payments or revenue that enables the use of other anthropogenic capitals and thereby underpins the provision of NCP.	Governmental direct payments to leave deadwood in forests. Bank loans to buy machinery.

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Isaac, R., Kachler, J., Winkler, K.J., Albrecht, E., Felipe-Lucia, M.R., Martín-López, B., 2022. Governance to manage the complexity of nature's contributions to people co-production, in: Advances in Ecological Research. Elsevier, p. S0065250422000095. https://doi.org/10.1016/bs.aecr.2022.04.009

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, in: Advances in Ecological Research. Elsevier, pp. 245–283. https://doi.org/10.1016/bs.aecr.2015.09.003

S2 Table. Coding set for the interview transcripts to elicit actor to actor relationships in the co-production of nature's contributions to people (NCP) in forests. Based on Isaac et al. (2022).

Category	*Code*	*Description*	*Definition (if applicable)*	*Selection*
1) general info	interview ID	identification number of the interview		number (continuous)
	coder	person coding the interview		RI, JK, BML
	exploratory	name of the exploratory		SCH; HAI; ALB
	verbatim	verbatim describing the actor to actor relationship, the NCP, and anthropogenic capital		text
2) actor to actor relationship	actor A	anonymised acronym of actor A		text
	actor group A	actor group to which this actor belongs		text
	level actor A	governance level at which actor A operates		SCH; HAI; ALB, Brandenburg; Thuringia; Baden-Württemberg; Germany; European Union
	actor B	anonymised acronym of actor B		text
	actor group B	actor group to which this actor belongs		text
	level actor B	level at which actor B operates		SCH; HAI; ALB, Brandenburg; Thuringia; Baden-Württemberg; Germany; European Union
3) NCP group	NCP group	category to which the co-produced NCP belongs		material; regulating; non-material

	NCP (in words)	verbatim describing the NCP in words		text
	Individual NCP	grouped individual NCP relevant for this study		timber production; climate regulation; habitat creation and maintenance; non-material NCP
4) anthropogenic capitals	human capital category	category to which human capital belongs to (if applicable)	Human capital refers to people's capabilities including health, informal knowledge, formal knowledge, skills, motivation, and labour that can yield a flow of NCP (Goodwin, 2003; Palomo et al., 2016).	labour; knowledge; skills; other HC
	human capital description	verbatim describing the human capital indicator in words		text
	social capital category	category to which social capital belongs to (if applicable)	Social capital includes all intangible assets associated with interactions between people including formal and informal networks, trust, and formal and informal institutions required for enhancing the flow of NCP. (Palomo et al., 2016)	networks; informal institutions; other SC
	social capital description	verbatim describing the social capital indicator in words		text
	physical capital category	category to which physical capital belongs to (if applicable)	Physical capital refers to technological or manufactured assets that contribute to the flow	tools and machinery; infrastructure and built capital; other PC

		of NCP (Goodwin, 2003; Palomo et al., 2016; Pretty, 2003).	
physical capital description	verbatim describing the physical capital indicator in words		text
financial capital	category to which financial capital belongs to (if applicable)	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 that contribute to the flow of NCP. (Palomo et al., 2016)	direct payments; subsidies; other FC
financial capital description	verbatim describing the financial capital indicator in words		text

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S3 Table. Mean values for degree, betweenness, and eigenvector of actor groups contributing to the overall NCP network and each focal NCP network (timber production, climate regulation, creation and maintenance of habitat, non-material NCP). Bold values represent the actor group with the highest mean value for the respective centrality metric. Mean values with letters (a, b) indicate actor groups with significant differences to others based on Dunn's multiple comparison test ($p < 0.01$). The level of significance based on Kruskal-Wallis test is indicated for 1% (***), 5% (**), and 10% (*).

Nature's contributions to people	**Centrality metrics**	**Biodiversity Exploratories**	**Foresters**	**Forest industry**	**Forest owners**	**Government**	**Protected areas**	**Societal actors**	χ^2
All NCP	Degree	54.50^{a}	57.39^{b}	49.54^{a}	**77.13^{b}**	61.50^{b}	64.25^{b}	30.84^{a}	19.70***
	Betweenness	**97.00^{b}**	58.13^{ba}	45.54^{a}	85.50^{b}	57.87^{a}	61.50^{ab}	31.32^{a}	23.39***
	Eigenvector	64.00	55.61	47.35	63.75	59.37	54.38	39.44	7.15
Timber production	Degree	6.50	36.88	44.68	55.50	33.36	6.50	28.60	10.05
	Betweenness	7.00	39.59	39.09	50.50	30.14	7.00	33.60	7.91
	Eigenvector	8.00	37.78	36.50	47.50	36.93	4.50	36.40	5.26
Climate regulation	Degree	23.50^{a}	20.63^{a}	10.00^{a}	24.00^{a}	24.44^{a}	**26.33^{a}**	11.93^{a}	11.20*
	Betweenness	35.00	21.17	10.50	25.17	21.25	24.50	13.00	10.35
	Eigenvector	34.00	16.96	24.50	21.00	21.75	16.67	16.93	4.13
Creation and maintenance of habitat	Degree	44.00^{ab}	33.62^{a}	16.50^{a}	37.75^{ab}	45.27^{b}	**53.17^{b}**	29.69^{a}	13.00**
	Betweenness	51.00^{ab}	34.20^{a}	17.33^{a}	37.50^{ab}	45.64^{b}	**54.00^{b}**	27.00^{a}	14.50**
	Eigenvector	40.00	32.93	27.67	29.75	41.59	45.33	33.81	3.55
Non-material NCP	Degree	10.50	20.75	10.50	10.50	23.57	17.00	23.14	5.02
	Betweenness	10.50	20.75	10.50	10.50	24.36	15.88	23.05	5.53
	Eigenvector	24.50	18.36	27.50	11.00	23.43	18.00	21.50	3.12

S4 Table. Mean values for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the co-production of the NCP **timber**. Bold values represent the actor group with the highest mean value for the respective centrality metric. Mean values with letters (a, b) indicate actor groups with significant differences to others based on Dunn's multiple comparison test ($p < 0.01$). The level of significance based on Kruskal-Wallis test is indicated for 10% (*).

Anthropo-genic capitals	**Centrality metrics**	**Biodiversity Exploratories**	**Foresters**	**Forest industry**	**Forest owners**	**Government**	**Protected areas**	**Societal actors**	χ^2
Human capital	Degree	8.00	33.22	42.33	28.33	23.50	8.00	21.75	10.23
	Betweenness	9.00	34.56	37.11	32.00	20.38	9.00	24.50	8.84
	Eigenvector	5.50	33.53	33.89	11.83	34.94	7.50	28.25	8.45
Social capital	Degree	-	28.76	22.50	39.38	34.27	14.50	22.80	6.59
	Betweenness	-	30.54	20.72	36.38	32.92	14.50	23.00	6.11
	Eigenvector	-	28.26	23.00	32.88	35.85	8.50	26.70	5.40
Physical capital	Degree	-	24.77	34.00	24.00	22.11	-	37.00	5.23
	Betweenness	-	26.30	31.70	26.50	18.78	-	38.00	5.12
	Eigenvector	-	25.33	25.70	27.00	27.56	-	40.50	2.06
Financial capital	Degree	-	10.60[a]	10.75[ab]	**21.50[b]**	14.50[ab]	-	-	7.79*
	Betweenness	-	11.70[a]	11.75[ab]	**21.38[b]**	12.689[ab]	-	-	7.07*
	Eigenvector	-	13.00	11.00	16.50	13.88	-	-	1.12

S5 Table. Mean values for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the NCP **regulation of climate**. No analysis was performed for physical capital contributing to the co-production of this NCP as too few connections were found. Bold values represent the actor group with the highest mean value for the respective centrality metric. Mean values with letters (a, b) indicate actor groups with significant differences to others based on Dunn's multiple comparison test ($p < 0.01$). The level of significance based on Kruskal-Wallis test is indicated for 10% (*).

Anthropo-genic capitals	**Centrality metrics**	**Biodiversity Exploratories**	**Foresters**	**Forest industry**	**Forest owners**	**Government**	**Protected areas**	**Societal actors**	χ^2
Human capital	Degree	5.00	8.60	5.00	-	-	-	5.00	5.04
	Betweenness	5.00	8.60	5.00	-	-	-	5.00	5.04
	Eigenvector	**10.50[a]**	5.70[a]	**10.50[a]**	-	-	-	4.50[a]	7.70*
Social capital	Degree	-	8.14	7.00	11.00	9.00	14.00	7.00	5.18
	Betweenness	-	8.00	7.00	11.75	9.38	13.33	7.00	4.65
	Eigenvector	-	9.00	13.50	10.75	10.00	9.33	5.00	1.72
Physical capital	Degree	-	-	-	-	-	-	-	-
	Betweenness	-	-	-	-	-	-	-	-
	Eigenvector	-	-	-	-	-	-	-	-
Financial capital	Degree	-	7.68	-	8.33	12.50	13.00	6.00	5.28
	Betweenness	-	7.83	-	8.50	12.17	13.50	6.00	4.67
	Eigenvector	-	10.25	-	11.17	9.00	5.50	8.25	1.37

S6 Table. Mean values for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the NCP **creation and maintenance of habitat**. Bold values represent the actor group with the highest mean value for the respective centrality metric. Mean values with letters (a, b) indicate actor groups with significant differences to others based on Dunn's multiple comparison test ($p < 0.01$). The level of significance based on Kruskal-Wallis test is indicated for 5% (**), and 10% (*).

Anthropo-genic capitals	**Centrality metrics**	**Biodiversity Exploratories**	**Foresters**	**Forest industry**	**Forest owners**	**Government**	**Protected areas**	**Societal actors**	χ^2
Human capital	Degree	31.00	15.94	13.00	20.25	20.25	-	18.89	5.27
	Betweenness	30.00	15.67	13.00	20.75	22.50	-	18.94	5.81
	Eigenvector	24.00	14.67	15.00	16.00	28.50	-	20.89	6.71
Social capital	Degree	-	16.18[a]	10.00[a]	10.00[a]	14.07[a]	**26.17[a]**	10.00[a]	11.48**
	Betweenness	-	15.86[a]	10.00[a]	10.00[a]	14.86[a]	**25.50[a]**	10.00[a]	10.37*
	Eigenvector	-	18.86	12.00	6.50	12.14	16.50	14.00	5.87
Physical capital	Degree	-	11.42	10.50	10.50	10.50		12.70	1.17
	Betweenness	-	11.42	10.50	10.50	10.50		12.70	1.17
	Eigenvector	-	11.33	9.50	9.50	9.50		13.90	2.58
Financial capital	Degree		13.96	9.00	20.50	19.61	9.00	18.67	5.66
	Betweenness		15.18	9.00	18.50	18.06	9.00	19.00	3.39
	Eigenvector		17.29	13.75	17.50	16.06	9.00	12.68	1.74

S7 Table. Mean values for degree, betweenness, and eigenvector of actor groups regarding their use of the anthropogenic capitals contributing to the co-production of **non-material NCP**. Bold values represent the actor group with the highest mean value for the respective centrality metric. Kruskal-Wallis tests reported non-significant differences for degree, betweenness, and eigenvector between actor groups across interactions when using each of the anthropogenic capitals.

Anthropo-genic capitals	**Centrality metrics**	**Biodiversity Exploratories**	**Foresters**	**Forest industry**	**Forest owners**	**Government**	**Protected areas**	**Societal actors**	χ^2
Human capital	Degree	9.00	14.33	9.00	9.00	19.67	20.00	11.60	6.22
	Betweenness	9.00	14.22	9.00	9.00	19.67	21.00	11.60	6.46
	Eigenvector	19.50	11.33	15.00	7.50	18.50	21.00	13.05	5.06
Social capital	Degree	-	13.00	6.00	-	13.40	10.38	13.58	1.66
	Betweenness	-	11.81	6.50	-	14.80	10.38	13.92	2.20
	Eigenvector	-	12.06	16.00	-	15.70	9.00	12.17	2.32
Physical capital	Degree	-	10.61	9.50	9.50	9.50	9.50	15.17	6.08
	Betweenness	-	10.61	9.50	9.50	9.50	9.50	15.17	6.08
	Eigenvector	-	10.17	6.50	6.50	16.83	10.00	13.00	4.83
Financial capital	Degree	-	6.30	-	-	9.50	11.50	9.00	2.20
	Betweenness	-	5.50	-	-	10.08	11.00	9.25	3.99
	Eigenvector	-	8.00	-	-	9.08	9.00	8.13	0.19

Appendix 6: Author declarations

Eigenständigkeitserklärung

In Bezug auf *Promotionsordnung der Fakultät Nachhaltigkeit der Leuphana Universität Lüneburg* erkläre ich, Roman Isaac, dass ich mich zum jetzigen Datum noch keiner Doktorprüfung unterzogen oder mich um die Zulassung zu einer solchen beworben habe.

Hiermit versichere ich, dass ich die vorliegende Dissertation mit dem Titel *More than trees Governing anthropogenic assets for nature's contributions to people in forests* nur in diesem laufenden und keinem anderen Promotionsverfahren eingereicht habe, diese noch keine*r anderen Fachvertreter*in vorgelegt habe und, dass diesem Promotionsverfahren noch kein anders endgültig gescheitertes Promotionsverfahren voran gegangen ist.

Des weiteren, versichere ich, dass ich die eingereichte Dissertation *More than trees Governing anthropogenic assets for nature's contributions to people in forests* eigenständig und ohne unerlaubte Hilfsmittel verfasst habe. Alle Textstellen, die sinngemäß oder als Zitat anderen Quellen entnommen sind, habe ich nach bestem Wissen und Gewissen im Text mittels Zitation kenntlich gemacht.

Hamburg, 11. Januar 2024

Ort und Datum

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