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# Expanding ecosystem multifunctionality measures to operationalize the IPBES framework

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## Abstract

Addressing interlinked societal and ecological challenges requires interdisciplinary approaches, such as those promoted by the IPBES framework. Yet, because of the conceptual and methodological challenges posed by interdisciplinary work, applications of the framework have been mostly qualitative. Here, we propose a net balance of NCP (netNCP) approach, that quantitatively represents multiple components of the IPBES framework. This adapts existing ecosystem service multifunctionality approaches to weight NCP supply by its relative priority by people to measure the overall benefit derived from nature. We expand existing approaches by integrating detrimental NCP, issues of access to NCP, and detailed supply-benefit relationships. We also offer perspectives for better integrating social and anthropogenic drivers, and their impacts on the components of netNCP. Overall, the netNCP approach provides a more robust and complete basis for the integration of ecological and social sciences. Such approaches are needed to quantify socio-ecological systems and to identify sustainable management options.

## Glossary

**Nature's contributions to people (NCP).** All the contributions both positive and negative of nature to people's quality of life<sup>1</sup>. **Benefits**, i.e. positive contributions, are broadly comparable to ecosystem services; and **detriments**, i.e. negative contributions, broadly comparable to ecosystem disservices.

**Stakeholder:** Any person who manages or receives beneficial or detrimental NCP, either directly or indirectly. Stakeholders can be classified into interest groups of individuals with similar patterns of NCP prioritisation and management activities<sup>2</sup>.

**NCP value:** Value can be defined as “a *principle* associated with a given worldview or cultural context, a *preference* someone has for a particular state of the world, the *importance* of something for itself or for others, or simply a *measure*”<sup>3</sup>. Here we focus on:

- **NCP demand:** The *amount* of NCP required or desired by society<sup>4,5</sup>. Different from demand in economics, which depends on one’s budget allocation between different NCP, here it is the total sum desired regardless of ability to buy, access, or compromise between NCP.
- **NCP prioritisation:** The *relative importance* of NCP to a stakeholder<sup>4,6</sup>, either positively (higher values of beneficial NCP are valued) or negatively (lower values of detrimental NCP are valued). All prioritised NCP can be considered demanded to at least some level. A NCP can have a high demand but low priority (for instance when the supply is abundant enough to meet the needs and thus not seen as a priority) and conversely.
- **Supply-benefit/detriment relationships** are also part of the valuation process. A supply-benefit relationship is a mathematical function that describes the relationship between accessible NCP supply, and human benefit (including both material and non-material benefits). The function can take a range of forms and is positive when the contribution is positive (beneficial NCP) and negative when the contribution is negative (detrimental NCP). The benefit measure of the supply-benefit/detriment relationship is broadly equivalent to utility in economics.

**Potential NCP supply:** The NCP supply produced by the ecosystem that could potentially be used if there is no limit to access (“supply potential” in <sup>7</sup>)

**Access:** broadly defined as “the ability to derive benefits from things”<sup>8</sup>, here from NCP.

**Access filter:** Biophysical, individual, social or economic factors that limit the accessible NCP supply. This can range from infrastructure (access roads) to legal rights to access an area, or knowledge enabling the use of some resources.

**Accessible NCP supply:** The proportion of potential NCP supply that is accessible to users and can be benefited from.

**NCP co-production:** Joint contribution of nature and other anthropogenic assets resulting in the supply of NCP<sup>9</sup>. This includes resource mobilisation and exploitation <sup>7</sup> such as management and maintenance, harvest and post-harvest operations, physical access and cultural appreciation<sup>10,11</sup>. Here we focus on Nature-People co-production, rather than people-people co-production that is often used in socio-ecological or governance research<sup>12</sup>.

**Ecosystem service multifunctionality:** Simultaneous supply of multiple prioritised ecosystem services, relative to their human demand<sup>4,13</sup>

**Net balance of NCP** (or netNCP): The overall balance of ecosystem benefits and detriments experienced by a stakeholder (see section 3 for detailed description). The measure is broadly equivalent to ecosystem service multifunctionality<sup>4,13</sup>, but also includes detrimental NCP. Measured as the sum of the benefits and detriments from all considered NCP, weighted by their respective priority by stakeholders.

**Institutions:** rules that structure human interactions, these may take a range of forms including legal regulations and social norms - for a full definition see<sup>14</sup>.

# 1. Introduction

There is growing awareness that global environmental challenges cannot be solved by the natural sciences alone, leading to a surge in interdisciplinary research that addresses interlinked societal and environmental challenges<sup>15</sup>. To enable this work, many frameworks that describe Social-Ecological Systems (SES) have been developed<sup>16–19</sup>, and there is a parallel trend in the increasing availability of ecological, socio-economic, and cultural data that allow their operationalization<sup>20,21</sup>.

A much-used SES framework is that of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)<sup>1,9</sup>. This framework aims to integrate the full cycle of interactions from nature to human quality of life via nature's contributions to people (NCP), i.e. “all the contributions both positive and negative of living nature to people's quality of life”<sup>1</sup>; but also the feedback from social and anthropogenic drivers onto nature<sup>9</sup>.

The IPBES conceptual framework was designed primarily for the science-policy interface, and despite the widespread adoption of this framework within academic research, quantitative and integrated operationalization of the IPBES conceptual framework in real-world systems has, to date, been scarce<sup>22</sup>. This is partly due to the conceptual and methodological challenges posed by the integration of social and ecological concepts and data.

Here, we present a new approach to quantifying the links between the different components of the IPBES conceptual framework, that considers both social and ecological concepts, and builds upon the ecosystem service multifunctionality framework (hereafter multifunctionality; <sup>13</sup>). Multifunctionality is defined as the ability of ecosystems to simultaneously provide multiple NCP, relative to their prioritisation by stakeholders<sup>4,13</sup>. In this article, we present some of the current challenges to quantifying the interactions between SES components within the IPBES conceptual framework, before proposing some solutions, based on the multifunctionality approach.

## 2. Challenges in quantifying the IPBES conceptual framework

The great complexity of SES<sup>23</sup> is recognised by the IPBES conceptual framework, which is organised around six main components which interact and feedback into each other. Ecosystem structure and condition (“Nature”, Fig. 1 box 1) determines the supply of NCP (Fig. 1, box 2), which in turn affects people's quality of life (Fig. 1, box 3). These relationships are modulated by several factors, including anthropogenic assets (Fig. 1, box 5) and institutional drivers (Fig. 1, box 6) that can mediate, for instance, the human contribution to NCP (NCP co-production), such as physical and social access<sup>10</sup>. These social components can also affect natural and anthropogenic drivers (Fig. 1, box 4), which feed back into ecosystems. The very comprehensive nature of this framework necessitates great simplification of the complexity of SES as adequate qualitative or quantitative description of each linkage is methodologically demanding<sup>23</sup>.

To date, quantification of the IPBES framework components has been mostly undertaken within the natural sciences, with most work concentrated on the relationships between *Nature* and *NCP* (Fig. 1; box 1 -> 2), and between *Direct Drivers* and *Nature*<sup>24,25</sup> (Fig. 1; box 4 -> 1). By contrast, most links involving anthropogenic and societal aspects have been studied qualitatively, e.g. the links between *anthropogenic assets* and *NCP*<sup>26,27</sup> (Fig. 1; box 5 -> 2) and those between *Institutions and Indirect Drivers* to *NCP*<sup>28</sup> (Fig. 1; box 6 -> 2, 3). In addition, quantitative assessments of the relationships between *Nature and NCP* (e.g. Fig. 1; box 1 -> 2) or between *Direct drivers and Nature* (Fig. 1, box 4 -> 1) often only investigate individual NCP, rather than integrating multiple (but see <sup>29-32</sup>). As a result, they are unable to capture the complexity of ecosystem-NCP relationships, measure the synergies and trade-offs between multiple NCP, or quantify the overall impact of ecosystem changes on people's quality of life.

Besides, while NCP include both positive and negative contributions<sup>1</sup>, little work has considered detrimental NCP<sup>33</sup>. Yet multiple studies have highlighted the impact of detrimental NCP, such as pests, diseases, and ecosystem greenhouse gas emissions on human quality of life<sup>34-38</sup>. Thus, their integration is essential if we are to make NCP assessments representative of the overall relationship between nature and people.

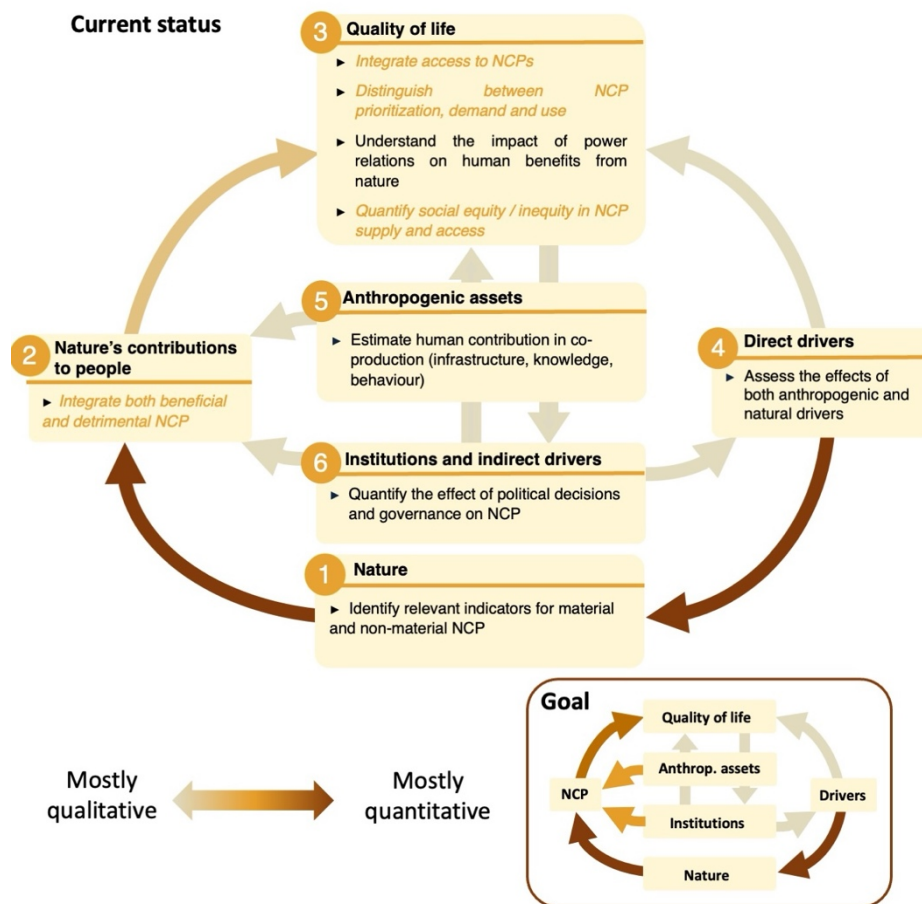
At the interface of natural and social sciences lies another challenge: relating NCP supply to the benefits and detriments that humans experience. First, the benefits and detriments received depend on the ability of people to access NCP supply because of limits imposed by biophysical, social, economic and institutional factors<sup>39,40</sup>. Access can vary widely across individuals and groups and can strongly affect the benefits that each perceives<sup>41</sup>. Yet, access is rarely accounted for in NCP research.

Another major limitation in quantitative NCP evaluation is capturing the many values of nature<sup>42</sup> in comparable metrics. There is a need to acknowledge both the material and non-material benefits derived from multiple NCP (as proposed in socio-cultural valuation techniques<sup>2,43,44</sup>) to allow for the quantitative comparison and integration of the multiple values of nature<sup>45</sup>. Yet, most NCP studies use valuation methods that are hard to transfer across the multiple types of NCP. Economic assessments, which estimate the monetary benefits obtained at any given level of supply<sup>46,47</sup>, are best-suited to value material NCP<sup>48</sup>. For instance, benefits from agricultural production can be broadly estimated as the product of yield and market value, minus production, processing and marketing costs<sup>49</sup>. Some studies have also proposed monetary valuation methods for non-material NCP, including the natural capital accounts, which estimate market prices for non-marketable NCP<sup>50</sup>. Examples include the medical costs avoided by obtaining physical and mental health benefits from being in contact with nature<sup>51</sup> and the travel costs incurred by people when visiting nature<sup>52,53</sup>. However, such approaches are considered contentious as they do not represent the diversity of values associated with NCP<sup>54</sup>. For instance, they poorly represent the intangible benefits of non-material NCP<sup>54</sup>, e.g. people's sense of place associated with a particular ecosystem<sup>55</sup>.

Finally, perhaps the largest challenge is in quantitatively integrating the wider social system with that of the typically quantified natural components of the SES. Addressing this issue requires linking changes in NCP and quality of life to changes in the numerous components of the human social system, including economics, institutions, governance, values and

technology. These can impact multiple of the above-mentioned components, including ecosystem management, via a range of pathways such as policy changes, access through e.g. legal rights, or valuation of different NCP. These aspects are rarely represented quantitatively, and thus often difficult to integrate with that of NCP research.

This list of challenges, while non-exhaustive, highlights the need for a quantitative approach that integrates aspects of NCP supply, access, and valuation. In the sections that follow, we introduce the current multifunctionality framework and describe its expansion to meet some of these challenges.



**Figure 1.** Structure of the IPBES conceptual framework, adapted from Diaz et al. 2015, showing some of the major challenges in quantifying each component. The framework recognises six main components that interact and feedback into each other. Ecosystem structure and condition determine the supply of NCP, which in turn affects quality of life. These relationships are modulated by the combination of anthropogenic assets and institutional drivers. These human components impact natural and anthropogenic drivers of nature, which feed back into ecosystem functioning. Challenges are shown in bullet points under the title of each component. The challenges specifically addressed in this paper are shown in orange type. The colour of the arrows indicates the current research underlying each of the links between components, from mostly qualitative to more quantitative. The objective of the approach is to provide ways to better quantify some links between NCP and quality of life, anthropogenic assets and institutions/indirect drivers and NCP. The inset Goal box indicates the new degree of quantification if the suggested framework is implemented

### 3. Expanding the multifunctionality framework

Recently, interest in quantifying the simultaneous supply of multiple NCP has led to the adoption of multifunctionality metrics, originally devised for biodiversity research<sup>56,57</sup>. One of these metrics, ecosystem service multifunctionality, integrates human and natural components by quantifying the simultaneous supply of multiple NCP, weighted by their prioritisation by people<sup>4,13</sup>, and accounting for the amount supplied relative to demand. In this context, prioritisation represents one element of valuation, which corresponds to the relative importance that people give to individual NCP (see below). As supply measures can be linked to ecosystem conditions, the overall impact of environmental and land-use changes on stakeholder groups can be assessed<sup>4,58,59</sup>.

In its present form, the multifunctionality approach comprises several steps, which largely match the widely-used cascade model of ecosystem services research<sup>60</sup> (hereafter NCP cascade), taking into account environmental processes and conditions, as well as NCP, their societal value, and impact on quality of life (Fig. 2, box 1-3). First, all major beneficial NCP (“ecosystem services” in the original framework, here NCP terminology) in a region are identified and their supply is quantified across the considered environmental gradients (e.g. across land use types). Thereafter, the NCP prioritisation is obtained from stakeholders using a standardised scoring technique. NCP supply is then converted into benefits received by stakeholders through a ‘supply-benefit’ relationship. Finally, the benefit scores obtained through the supply-benefit relationship are standardised and multiplied by priority scores representing the relative priority of each NCP to each stakeholder group. This gives each group a measure ranging from 0-1, where 1 means all NCP are provided at their maximal levels. We propose that this multifunctionality approach can be extended to quantify the “net balance of NCP” (netNCP), thus making it consistent with the general IPBES conceptual framework (Fig. 2).

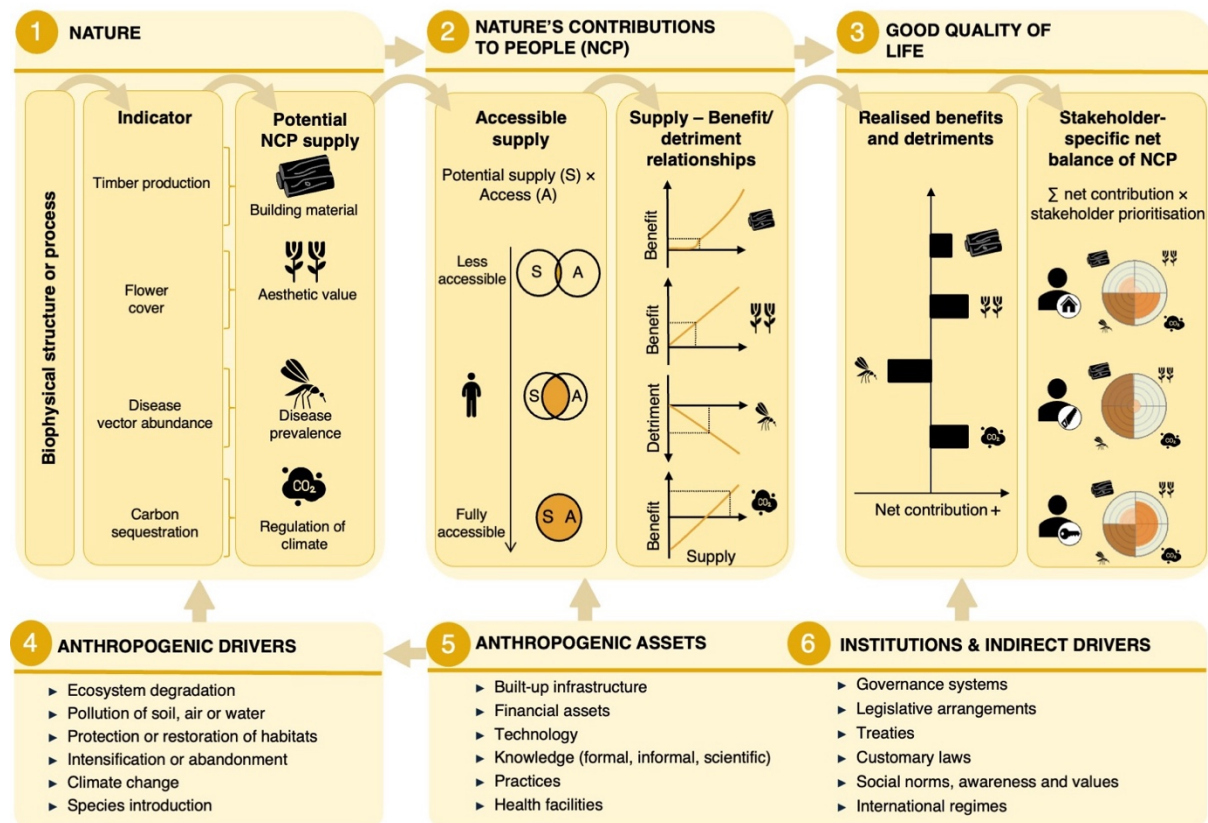
In the following sections, we show how to quantify the netNCP and link this measure and its underlying components to numerous aspects of the social system. To do this we show how the multifunctionality approach<sup>13</sup> can be adapted and expanded to integrate with the IPBES conceptual framework. Specifically, we expand the current multifunctionality approach in four directions:

1. Include detrimental NCP (previously excluded from multifunctionality assessments), thus deriving an overall measure of the net balance of both benefits and detriments: netNCP (Fig. 2, box 1).
2. Incorporate access to NCP supply, by adjusting the potential supply of a given NCP to the supply that is effectively experienced via an ‘access filter’, i.e. accessible supply (Fig. 2, Box 1). This supports more realistic assessments that consider the level of supply actually available to, or experienced by, stakeholders.
3. Provide a formal quantitative framework for linking the supply of benefits/detriments to material and non-material benefits and detriments: the supply–benefit/detriment relationship. This is a key bridging component in linking ecosystem NCP supply to human quality of life.



4. Finally, we highlight directions for further integration of netNCP metrics into SES studies. Specifically, we point towards the need to incorporate a wider range of co-production factors that alter the NCP cascade, and to quantify and represent the interface between the social system and the NCP cascade in greater detail, which is the first step towards assessing the impact of changes in the social system (such as in governance and economics). We also stress the need to incorporate temporal dynamics into the netNCP approach.

Since the most appropriate data acquisition methods are likely to differ depending on the scale of analysis, we present a framework that is tailored for relatively small SES scales, ranging from village to province. We also provide a worked-through example of this expansion (Box 1).



**Figure 2.** Integration of the netNCP approach within the IPBES conceptual framework. Each component of the IPBES conceptual framework (Fig 1) relates to one or more netNCP components. Altogether, boxes 1-3 provide the overall quantification of netNCP, which can help identify key direct and indirect drivers of change (boxes 4-6).

### 3.1 Selection of NCP and their indicators (Fig. 2 box 1)

The starting point in measuring netNCP is the identification of all NCP relevant to stakeholders (identified through stakeholder analyses), and their means of quantification using appropriate indicators (Fig 2, box 1). This can be done through focus group discussions, workshops or interviews in which relevant stakeholders list the different NCP that they demand<sup>2,61</sup>. Particular attention should be given to non-material and detrimental NCP, which are often overlooked in NCP assessments<sup>34,61,62</sup>. Omitting these risks misrepresenting the benefits provided by nature

to society, and biasing the assessments towards certain NCP or stakeholders. The final list of NCP can rely on global NCP classifications such as the one proposed by IPBES<sup>9</sup> but should be tailored to local contexts, for instance by using interviews and focus group discussions to identify all context-specific detrimental and beneficial NCP that are prioritised by local stakeholders<sup>55,63</sup>. These should be restricted to NCP that directly affect stakeholders (“final benefits”<sup>60</sup>) rather than those that underlie other NCP to avoid double-counting of some NCP. For instance, pollination usually does not benefit stakeholders directly, but indirectly by underpinning the production of many crops; it should not be included so as not to overemphasise the importance of this NCP to people.

Once a list of all NCP is produced, reliable and context-relevant indicators should be identified for each NCP. While there has been significant progress in identifying indicators for beneficial NCP in the past years<sup>47</sup>, such assessments are lacking for non-material and detrimental NCP (but see<sup>64</sup>). For non-material NCP, participatory approaches such as photo-elicitation<sup>65</sup> can be used to identify appropriate indicators, e.g. ecosystem components that are culturally valued<sup>66,67</sup>. Meanwhile, suitable data may already be available for many detrimental NCP, though in literature that are often not included in the SES discourse, such as human-wildlife conflicts<sup>38,68</sup>, zoonotic diseases<sup>69</sup> or agricultural pests<sup>70</sup>. While as many NCP as possible should be included for a complete and representative assessment, efforts should particularly be concentrated to obtain reliable indicators for the NCP identified by stakeholders as having the highest impact on their well-being<sup>71</sup> and/or highest priorities, as these will have the largest impact on netNCP. When site-level data is unavailable, values can be estimated from process-based, phenomenological or proxy-based models<sup>72</sup>, especially for less prioritised NCP.

Finally, these indicators or proxies are converted into supply estimates. If only one indicator per NCP is available, this can be as simple as equating NCP supply to the value of the indicator. When multiple indicators are available for a single NCP (e.g. taxonomic and functional diversity for the aesthetic value of coral reefs<sup>73</sup>), they can be scaled, weighted by their importance, and averaged into an estimate of overall supply.

## 3.2 From NCP supply to benefits (Fig. 2 box 2)

### *Accounting for access to NCP*

The NCP supply estimated from the above-mentioned indicators usually corresponds to *potential supply*, i.e. the maximum NCP supply produced by the ecosystem that could potentially be used (“supply potential”<sup>74</sup> (Spangenberg et al., 2014b)). In reality, while the potential NCP supply depends on ecosystem condition, the *accessible supply*, i.e. that which is actually usable, depends on the ability of stakeholders to access NCP supply (Fig. 2 box 2). Access can be broadly defined as “the ability to derive benefits from things”<sup>75</sup>. In addition to physical limitations (e.g. absence of roads or steep slopes), access can thus also be affected by knowledge (e.g. ability to identify useable species), socio-cultural factors such as traditions (e.g. prevention of use by cultural taboos), and economic and institutional factors (e.g. lack of financial capital to fund resource extraction, legal rights to access an area for recreation). Any of these dimensions of access can be shaped by power relations among stakeholders<sup>74–77</sup>. When

access can be an issue, we therefore suggest applying an “*access filter*” into netNCP assessments. This adjusts the potential supply of a NCP (e.g. aesthetic value of a whole landscape) by that which is accessible (e.g. proportion of the landscape that is open to visitors) to represent the accessible proportion of the potential supply (e.g. the proportion of aesthetically beautiful land that is viewable) (Box 2, step 2).

While we present the access filter as a simple proportion here (Box 1), effort may be required to estimate stakeholder- and context-specific access filters in practice, e.g. by only considering socially known species from supply measures of medicinal plants production, or estimating the proportion of supply that falls within geographic boundaries. Access drivers, such as enforcement and security of property rights, are often complex and expansion is required to link these aspects to our framework.

### *Linking NCP supply to material and non-material benefits*

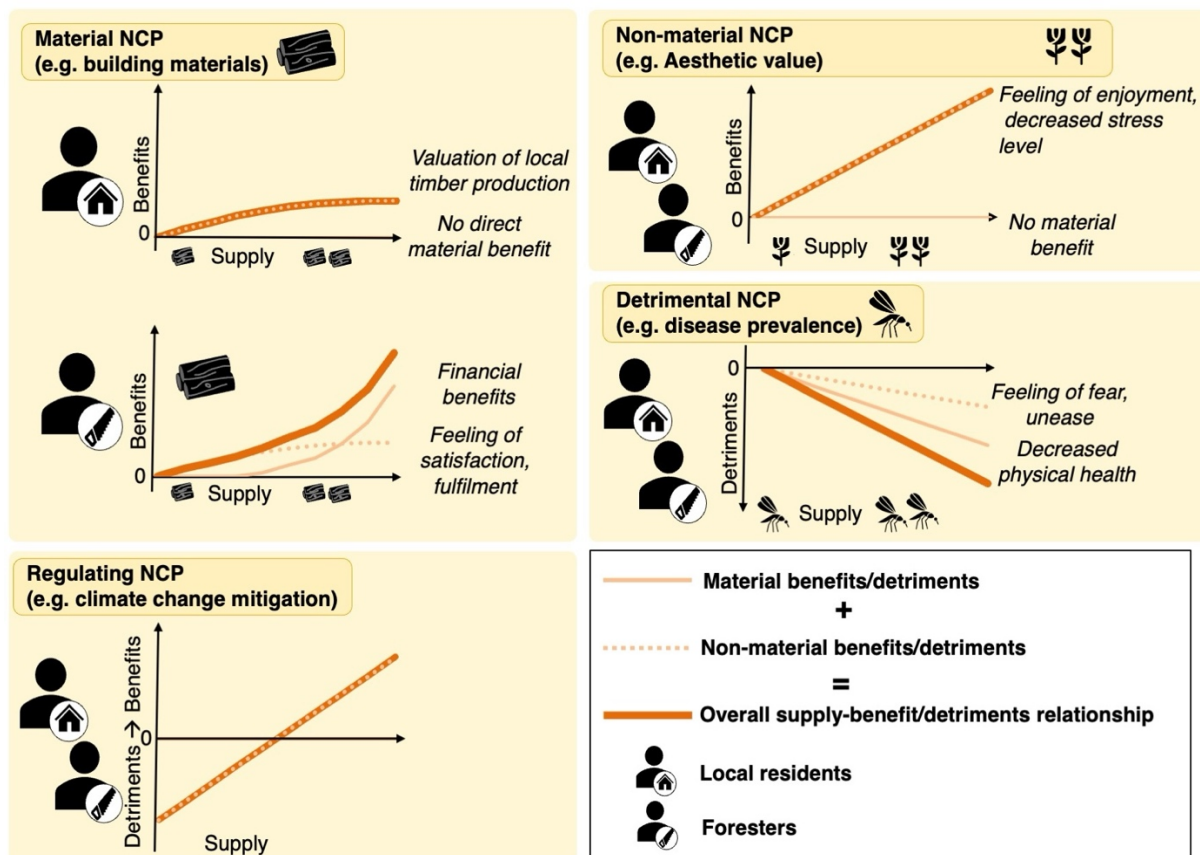
Once accessible supply has been estimated, the next key challenge in evaluating netNCP is to determine the benefit, or detriment, that stakeholders derive from a particular level of supply. This is described by *supply-benefit relationships*, which mathematically describe how rising supply levels of beneficial NCP are related to benefit experienced by people<sup>13</sup>. These can be extended to detrimental NCP, by allowing the relationship to be negative, or to become negative at certain levels (i.e., benefits decrease as supply increases, or decrease beyond an optimum). The latter approach allows us to go beyond the false dichotomy of beneficial and detrimental NCP<sup>78</sup> by allowing some NCP to switch between being detrimental or beneficial at certain levels. For instance, ecosystem carbon fluxes can be either beneficial (positive sequestration rates) or detrimental (negative sequestration rates, i.e. emission, Fig. 3). This can be represented by a supply-benefit relationship that gives negative and detrimental scores when ecosystems emit carbon, and positive benefit scores as the system switches to sequestration.

In addition to the direction and sign of the supply-benefit relationship, a robust estimation of the form of this relationship is important to accurately describe the actual benefits and detriments experienced. In practice, previous multifunctionality studies have usually assumed a positive and linear relationship between supply and benefits, usually due to a lack of data on the real relationship<sup>4,59</sup>. While the assumption that benefits increase linearly with supply is probably safe for NCP that operate at large scales (e.g., climate regulation via carbon storage<sup>13</sup>), other NCP are more likely to display non-linear supply-benefit relationships. These include NCP with direct economic benefits: for instance, under a certain level of wood production, exploitation of a forest parcel might not be economically viable and will be discontinued resulting in null benefits; while above the threshold increasing production could deliver increasingly large returns due to economies of scale (Fig. 3a). Similarly, benefits from regulating NCP could saturate (e.g. water supply exceeding consumption) or become detrimental (e.g. excess rainfall turning into floods) beyond a certain threshold. Such thresholds can help assess how NCP supply relates to the overall NCP demand, i.e. how much of a NCP is needed to fully meet stakeholders’ needs.

A range of methods to assess the shape of supply-benefit relationships have been described, e.g. within the natural capital approach<sup>79</sup>. At its simplest, the shape of the relationship can be

based on expert knowledge: for instance, using a threshold relationship to describe that benefits derived from tree-provided shade stop increasing after 50%<sup>4</sup>. More quantitative estimations are likely to require complementary methods depending on the considered NCP, ranging from economic assessments<sup>50,79</sup> to socio-cultural valuation approaches<sup>80,81</sup>. These may be advanced if required by conducting additional surveys or relying on NCP use patterns<sup>82</sup> to assess how different groups may appreciate different NCP levels, or how demand shifts in response to supply. Whenever possible, complementary methods should be used to assess both the material (e.g. financial benefits from selling crop yield) and non-material (e.g. physical and mental health, social status) benefits related to each individual NCP. Further advances could involve a better representation of the costs of accessing NCP or competition for NCP, such that one person's benefit from an NCP limits the benefit received by others (as often true for provisioning services, e.g. limited amounts of timber) to link this framework to issues of resource management. Another extension would be better representation of interdependencies between the benefit provided by different NCP: for instance, the benefit level of non-essential NCP might only manifest when levels of essential NCP exceed critical levels.

The *NCP accessible supply* can then be transformed through the corresponding supply-benefit/detriment relationship, with *final benefit and detriment* scores ranging from -1 (maximum detriments) to 1 (maximum benefits) for each NCP.



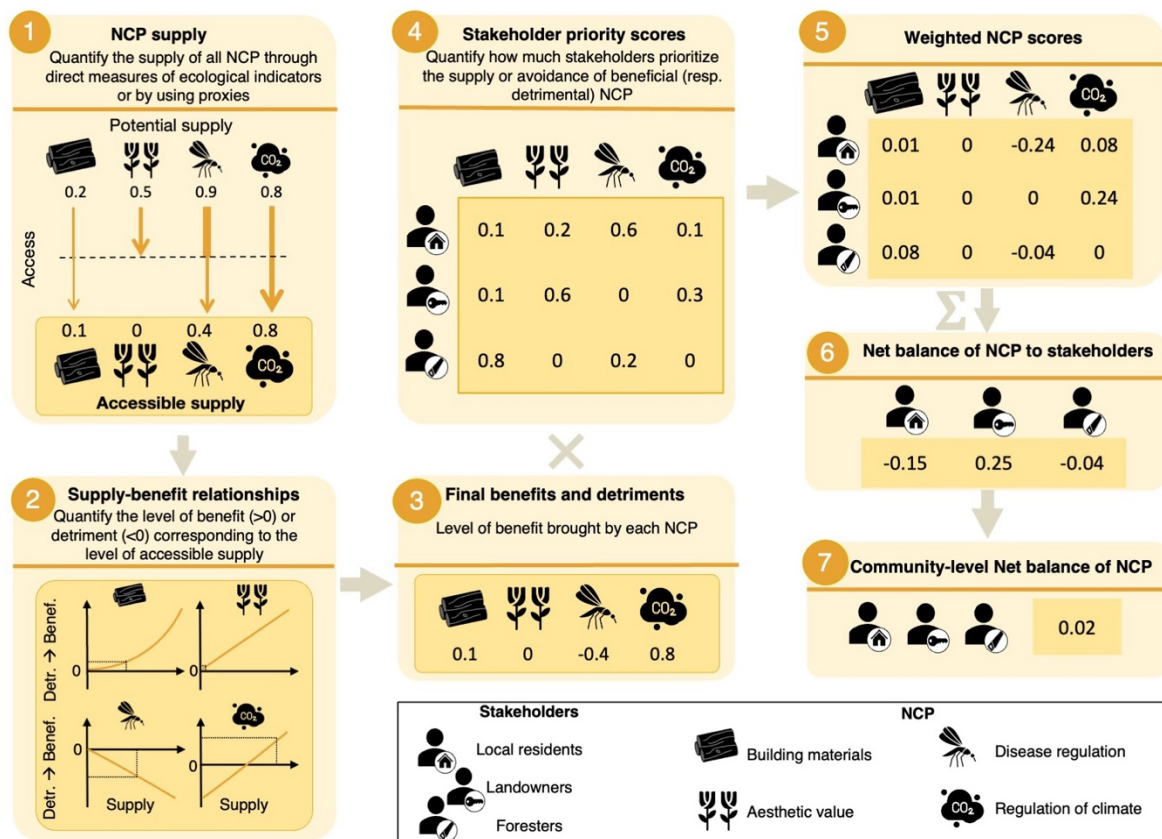
**Figure 3.** Combining material and non-material benefits and detriments into standardised supply-benefit/detriments relationships. Here we provide examples for two stakeholder groups (locals and foresters) for three NCP (timber production, aesthetic value, and disease prevalence). Material benefits/detriments can be assessed for each value of NCP supply through a range of methods including economic assessments<sup>50</sup> and should ideally be complemented by additional approaches<sup>43</sup> to assess the non-material benefits/detriments accompanying

these benefits. Both material and non-material benefits will differ across stakeholders either qualitatively (e.g. local inhabitants receive no direct material benefit from the timber produced in their local environment) or quantitatively (e.g. slope and thresholds of the relationships can be income-dependent).

### 3.3 Measuring the net balance of NCP

To evaluate the overall balance of NCP (netNCP), final benefits and detriments must be weighted by their relative priority to people. This information can be obtained from quantitative surveys, in which respondents are asked to distribute a fixed total number of points across all NCP identified during the initial expert interviews or focus group discussions (section 3.1), according to how much they prioritise each single NCP<sup>2</sup>. While this can be done alongside the initial NCP identification process (section 3.1) it may be better performed as a second step, once the list is finalised and indicators identified. These priorities can be averaged across social groups, either predetermined (e.g. stakeholder groups) or data-driven (people with similar priority patterns)<sup>2</sup>. The relative priority of each NCP is then measured as the proportion of points attributed to it by each group, and is multiplied by the corresponding final benefits/detriment value to obtain weighted NCP scores. The weighted scores are then summed to obtain a *net balance of NCP* for each group, scaled between -1 (maximum supply of detrimental NCP, no beneficial NCP) and 1 (maximum supply of beneficial NCP, no detrimental NCP).

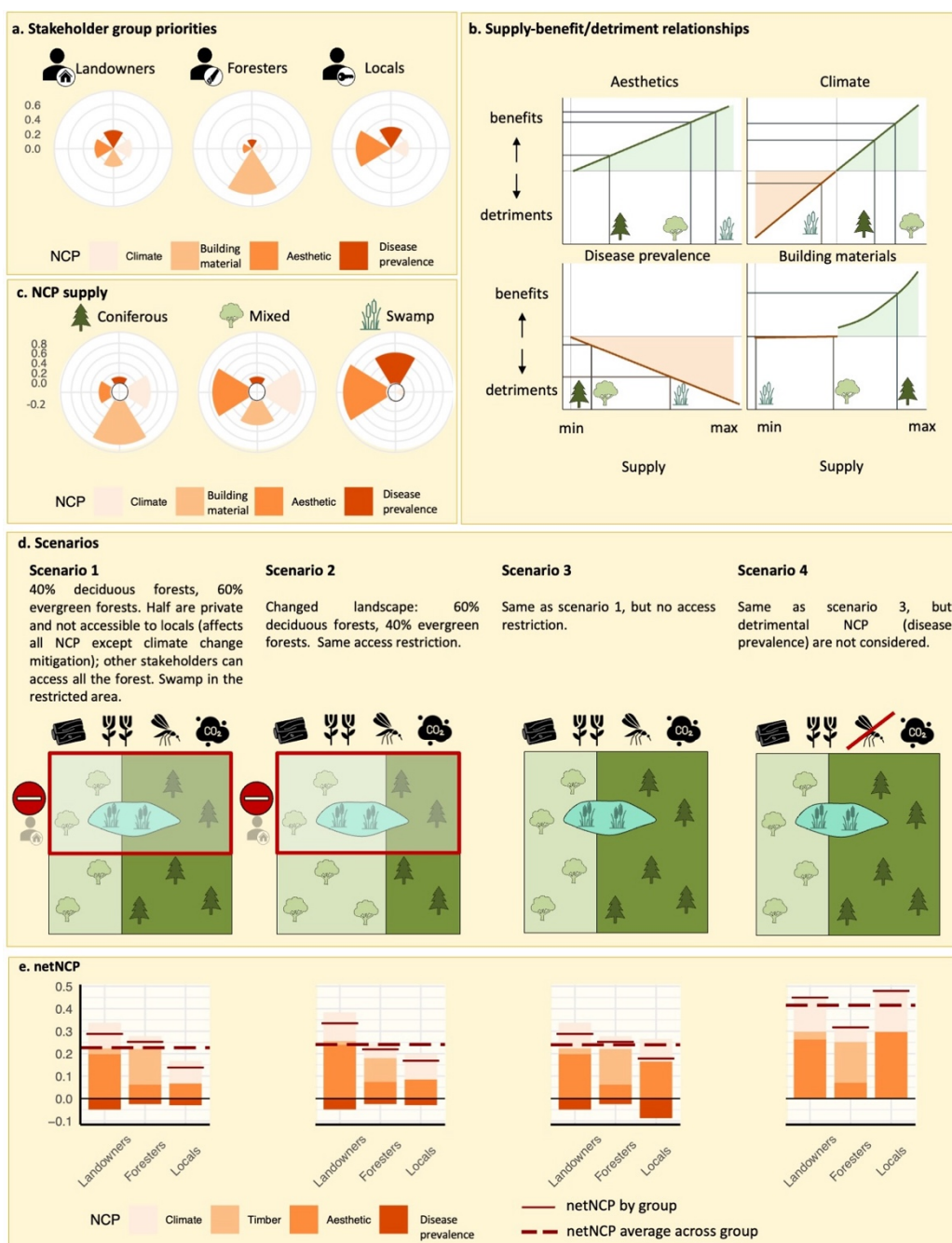
The resulting scores can be used to assess how well an ecosystem or landscape serves the needs of various stakeholder groups, incorporating multiple values. Comparative and modelling studies can also be used to estimate the effects of changes to ecosystem condition and societal priorities on the netNCP, as has been done for multifunctionality metrics<sup>59,83</sup>. Stakeholder-level netNCP scores can be averaged across stakeholders to estimate community-level netNCP or compared across groups to evaluate how equitably NCP are distributed across groups<sup>20</sup>.



**Figure 4:** Calculating netNCP step by step. The workflow integrates all components of netNCP from NCP potential and accessible supply, supply-benefit/detriment relationships, and priorities. Stakeholder scores shown represent averaged group values.

### Box 1. Applying the netNCP approach

Here we describe a hypothetical example to illustrate how the different components of netNCP can be integrated and how each component influences the net balance of NCP to stakeholders. A full tutorial with corresponding R code for the different steps can be found in the supplementary material. The panels of the corresponding figure show: (a) Relative stakeholder priorities for the four considered NCP. (b) Supply-benefit/detriment relationships for each NCP, here the relationships are assumed to be identical across stakeholder groups. The vertical lines indicate supply and corresponding benefits for the average supply in each land use type. The red areas denote detriments, the green areas denote benefits. (c) Potential supply of each NCP in the three considered land uses; values within the inner circle indicate negative supply (here, negative carbon sequestration i.e. negative emissions in swamps). (d) Scenarios of land-use change and access restriction change (see details below). (e) Resulting netNCP.



### Description of the hypothetical system

The hypothetical focus area is composed of coniferous, intensively managed tree plantations, mixed, extensively-managed forests and a swamp. We focus on three beneficial NCP (aesthetic value, carbon sequestration, building materials (timber) production) and one detrimental NCP (health risks, e.g. presence of disease vectors); and three stakeholder groups: foresters, landowners, and local residents. NCP differ in their degree of prioritisation by the different stakeholder groups (a) and supply by the three land use types (c). We assume different forms of supply-benefit/detriment relationships (b). Benefits from aesthetic value increase linearly with supply. Carbon sequestration leads to benefits when positive, and detriments when negative (i.e. carbon emissions). Detriments from health risks decrease linearly with supply, and benefits from timber production increase exponentially after a certain threshold of economic viability for harvest is reached (before which the benefits are null).

### Scenarios and results (d, e)

We explore four different scenarios. In **scenario 1**, the forest area is composed of 60% coniferous forests and 40% deciduous forest. Part of the area, covering the swamp and half the forests, is privately owned, which means local residents cannot access the NCP supplied there, except for carbon sequestration, which does not require access. Foresters and landowners can access the whole area. Because most of the area is covered with coniferous forests providing the high timber production prioritised by foresters, this scenario leads to a relatively high netNCP for foresters compared to other groups.

In **scenario 2**, the relative proportion of the two forest types change (to 60% deciduous and 40% coniferous; the access conditions remain the same as in scenario 1. The reduction of coniferous forest cover leads to lower netNCP for foresters, and slightly higher for locals, than scenario 1.

In **scenario 3**, the proportion of forest types is the same as scenario 1 but the access restrictions are lifted meaning local residents now access a larger supply of beneficial NCP, such as aesthetics. However, they can also access the swamp, which hosts disease vectors. The resulting increase in health risks compensate for the obtained benefits, resulting in a close-to-null change in netNCP.

In **scenario 4**, the proportion of forest types is the same as in 1 and 3 and the access restrictions are also lifted. However, the netNCP calculation does not include detrimental NCP, i.e. health risks. This results in much higher netNCP values, and a change in the repartition of netNCP values across groups.

This example provides a clear demonstration of the need to consider access, detrimental NCP and a wide range of stakeholder groups in NCP assessment and corresponding environmental decision making.

## 4. Future expansion of the netNCP approach

So far, we have shown how the netNCP approach can be used to quantify and formalise several interactions between the natural and human components of the IPBES conceptual framework. The impact of environmental drivers on netNCP (e.g. land-use, biodiversity and climate change; Fig. 1 box 4) is usually relatively well understood and represented<sup>59,83</sup>. However, changes in the social system, including those involving technologies, institutions, socio-economic variables, knowledge and values (Fig. 1 box 5, 6) have received less attention (but see <sup>28</sup>). A full discussion of the challenges in incorporating the social system into the netNCP approach is beyond the scope of this article, but here we discuss some potential first steps and present directions for further development.

Our first suggestion is to add a well-defined description of the interface between the natural and social systems. This allows us to see where changes in the social system can influence the netNCP cascade. Clues as to how this interface could be defined can be found in work describing ecosystem service co-production. In the IPBES conceptual framework co-production is the modification of natural ecosystem benefits by people's interactions with them, and by inputs from anthropogenic assets<sup>9</sup>. Co-production includes actions related to land-use change, which alters ecosystem condition; land condition and management, which alters potential supply via co-production; and also knowledge and legal or physical access, which could affect the access filter<sup>10,84</sup>. Such actions can thus be seen to form an interface with multiple components of the netNCP cascade (Fig 5). Other actions might affect the supply-benefit/detriment relationship, such as increased subsidies for sustainable forest management shifting the threshold of economic viability for wood production shown in Fig. 3. Once defined,



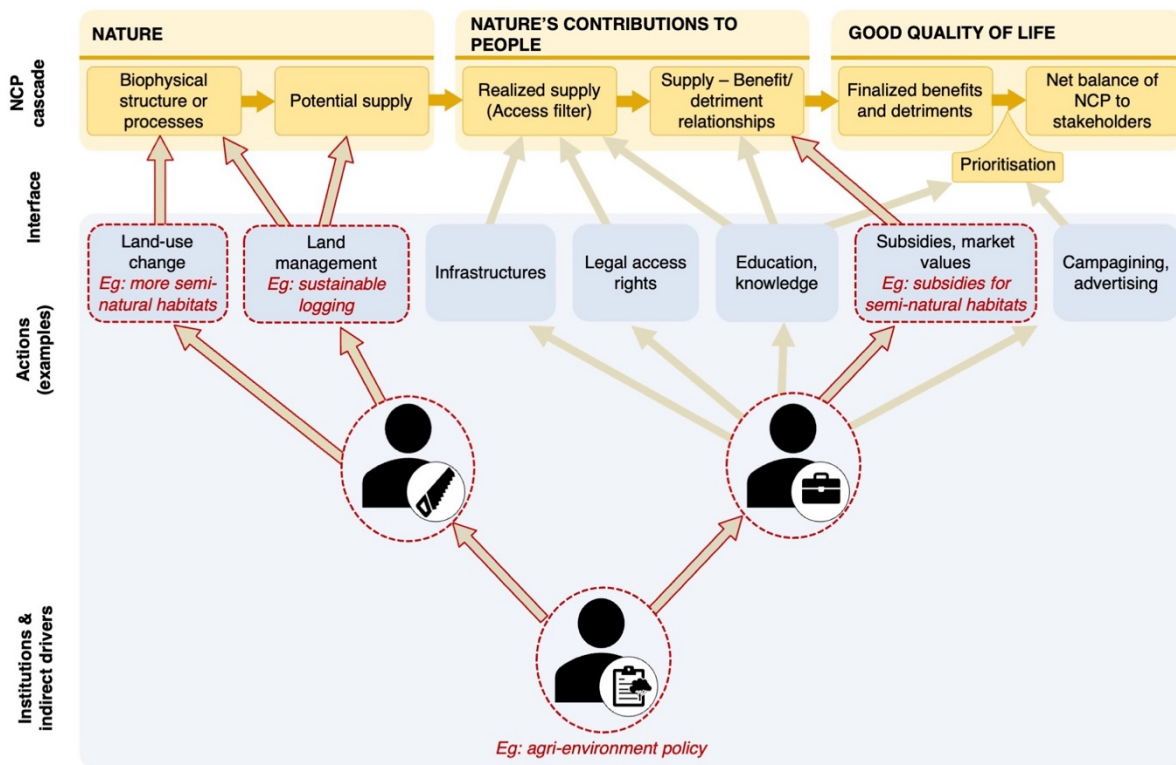
the impact of different actions along this interface can be investigated via modelling simulations or experiments. This could be an insightful means of determining how different changes to human actions would alter netNCP. For example, it would be possible to assess the sensitivity of overall netNCP to each action along the cascade by sequentially changing each netNCP parameter by a fixed proportion (e.g. +/- 10%) to simulate change in this factor. This could reveal which actions affect the final netNCP score most strongly, and how much any given change, e.g. to supply or access, would affect netNCP.

As a further extension, the system governing the actions at the interface could be defined. Depending on the action, this may take the form of economic or legal systems and/or social values and preferences<sup>40,85</sup>. For example, changes in income levels, market value, subsidies, or human demography could affect supply-benefit relationships, and campaigning and advertising could all alter prioritisation scores. (Fig 4). Such aspects of the social system are traditionally studied by disciplines with less established links to the environmental sciences, such as economics, psychology, political science and sociology. Quantitatively formalising the links between these social drivers and the netNCP framework requires collaboration and integration of these fields with each other and the natural sciences<sup>11</sup>. Connecting the NCP cascade to these disparate fields would also require the formulation of an agreed language and terminology. Given the complexity of this issue and to avoid the development of many parallel terminologies we suggest this is best done as part of a broad consensus building exercise, e.g. via IPBES itself.

To give a more specific example of how these expansions to the netNCP approach may operate in practice, consider a change in large-scale agri-environment policy, such as the European Union's common agricultural policy<sup>86,87</sup> (Fig 5). Expert knowledge from across disciplines could define the actions at the interface (e.g. farm management practices, access to land or market) and qualitative research could identify how a policy change might cascade from written policy to the actions of legislative bodies, farmers, and conservation groups to then impact actions along the cascade, including the abundance of different land cover types, fertiliser and pesticide use, and subsidy payments. This could provide estimates of the potential change for quantitative scenarios. These could then be implemented in the NCP cascade as changes in land cover and in NCP supply in the natural part of the cascade, and as change to the supply-benefit relationship for the subsidies (red arrows Fig. 5).

Finally, another important aspect missing from the existing netNCP approach is temporal dynamics and feedbacks between its components. The approach currently takes a 'snapshot' approach, with netNCP calculated for an existing state, and future states as a new equilibrium under scenarios of change. This may fail to capture real changes in NCP supply over a range of time scales, from instant to decadal and longer, due to ecological time-lags and/or legacy effects<sup>88</sup>, for example in the case of extinction debts<sup>89</sup>. As the drivers of change (either natural or anthropogenic) are currently considered as external to the system, feedback between the different components are also not considered. In real SES, feedbacks may take a range of forms, such as alteration of NCP supply following extraction and use, changes to land management as a result of current benefit levels<sup>90</sup>, variation in demand following supply change, or even feedbacks between climate, biodiversity and NCP<sup>91</sup>. Implementing these temporal dynamics

and feedbacks would bring additional insight and realism but requires careful consideration of the multiple mechanisms involved.



**Figure 5.** Identifying the impact of social change on the netNCP cascade. In the top part of the figure, the netNCP approach follows the cascade model<sup>60</sup> from nature to NCP and their value to society. This interfaces with the social system as various forms of NCP co-production. The case shown in red illustrates examples of large-scale agri-environmental policy change that impacts several actions at the social-natural system interface (see text for details).

## 5. Conclusion

Quantitative assessments of the relationships between humans and nature are needed to reliably inform decision makers of the impact of actions, and effectively support decision-making. While the ecosystem service multifunctionality approach allowed for the impacts of biodiversity and land-use change on overall NCP supply, numerous aspects, such as access, and detrimental NCP were not represented. The netNCP approach presented here has the potential to advance human-nature relationship assessments more broadly, by allowing for a wider quantitative integration of multiple different components of the IPBES conceptual framework. In comparison to multifunctionality approaches, the netNCP framework by including detrimental NCP proposes a more representative picture of the human-nature relationship, that may shed new light on conservation and ecosystem management conflicts. Further, it allows the role of a far greater range of factors, both biophysical and societal, to be assessed, and for the impact of changes in these factors to be investigated. The modular nature of the framework allows users to invest as much effort as required by the research question into

each component - making it adaptable to a range of issues and approaches. The netNCP thus provides a more robust and complete basis for the integration of ecological and social sciences that is needed to quantify SES and identify options for their more sustainable management.

### Author contributions

MN, ALB, GLP, SP, NRK, DGM, KDK, PM participated in early discussions to design the framework. MN, PM led the writing of the manuscript. All authors contributed critically to the manuscript.

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