Mapping the connections

An integrated approach to mapping Nature’s contributions to people in a Nordic biosphere reserve

Jarrod Cusens

Thesis for the degree of Philosophiae Doctor (PhD)
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SCIENTIFIC ENVIRONMENT

This PhD dissertation was written at the Department of Biological Sciences, Faculty of Mathematics and Sciences, University of Bergen. I am also affiliated the Centre for Sustainable Area Management (CeSAM), University of Bergen, Norway.

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ABSTRACT IN ENGLISH

Nature and her ecosystems make multiple contributions to people that benefit our wellbeing. These *ecosystem services* are under threat due to extensive human activities that have resulted in widespread land-use change, rapid climate change and destructive overharvesting. Acknowledging and valuing ecosystem services is a way to account for them in policy actions to manage ecosystems sustainably for people and nature. However, there are different ways in which ecosystem services can be valued across biophysical, socio-cultural, and monetary value-domains and these values interact within and across domains. To fully value ecosystem services there is a need to not only develop valuation methods across all three domains, but also ways of integrating across them. Ecosystem services are not evenly distributed, and their values differ in space due to various social and ecological factors. Therefore, to manage ecosystem services we also need to know how and why their values vary across landscapes, and we need to account for the dynamic relationship between ecosystem services across the value-domains and social-ecological contexts. In this thesis I present four papers that addresses some of these challenges with ecosystem services within the context of a UNESCO Biosphere Reserve in western Norway.

First, we mapped socio-cultural values for ecosystem services using a public participation geographic information systems (PPGIS) survey. We explored how socio-cultural values for ecosystem service values vary across a biosphere reserve, which values commonly co-occur in *bundles*, and what social-ecological characteristics determine the distribution of those bundles. People mapped predominantly places for outdoor recreation, biodiversity, agricultural products, and cultural heritage predominantly in areas with higher human populations. We identified five bundles representing linked biocultural values for agriculture and cultural heritage, outdoor recreation and biodiversity, and wild food and mental wellbeing. In general accessibility was the most important factor that determined the distribution of the bundles.

Second, we integrated biophysical values with socio-cultural values and mapped ecosystem services in the biosphere reserve. We explored the distribution of these integrated ecosystem services values across the biosphere reserve zones and their

bundles across two spatial scales. The ecosystem services bundled into three distinct social-ecological system archetypes that were similar in their distribution and relative ecosystem service values at both spatial scales. The bundles were also well matched to relative ecosystem services values of the Biosphere Reserve zones (core, buffer and transition) indicating that the bundles capture the social-ecological systems of the zones. These results show that it is important to consider the social-ecological context of the zones to provide sufficient knowledge to inform management.

Third, we used a novel combination of PPGIS and social network data to map the ecosystem co-production network in the biosphere reserve. We identified four components of the ecosystem co-production network as socio-cultural values, direct management, governance, and research/knowledge production. First, we mapped the relative attention different ecosystem services received from those co-production components. Then we mapped the social network of communication about different ecosystem services among the co-production components. We found mismatches between different components of the co-production network. Importantly, we identified that cultural ecosystems were highly valued but receive comparatively less governance and particularly research attention. Furthermore, the primary managers of cultural ecosystem services were also poorly connected in the ecosystem service co-production social-network. The results show the importance of thinking of ecosystem service co-production as a *relational network* and of mapping what is being discussed by whom.

Finally, we integrated ecological field surveys and PPGIS to explore the (mis)match in biophysical and socio-cultural values for ecosystem services in the context of land abandonment and afforestation. Biophysical values for ecosystem services were more similar across vegetation types while socio-cultural values were generally highest in open vegetation and unplanted forest types. The ecosystem service with the largest difference in biophysical and socio-cultural values global climate regulation, while biodiversity and agricultural products were similar across the value-domains. Socio-cultural values were not evenly spread across the study participants. There were two distinct groups representing older farmers resident in the region with high values for provisioning ecosystem services on the one hand, and non-resident younger females

valuing regulating and maintenance ecosystem services. This study shows the importance of considering different value-domains and the factors that influence those values in land-use change decisions.

Keywords: ecosystem services, public participation geographic information systems, mapping, biophysical, socio-cultural, valuation, UNESCO Biosphere Reserve, social-network, land-use change, Man and the Biosphere programme

SAMMENDRAG PÅ NORSK

Naturen og hennes økosystemer gir flere bidrag til mennesker som gagner vår velvære. Disse *økosystemtjenestene* er truet på grunn av omfattende menneskelige aktiviteter som har resultert i omfattende arealbruksendringer, raske klimaendringer og destruktiv overhøsting. Å anerkjenne og verdsette økosystemtjenester er en måte å gjøre rede for dem i politiske handlinger for å forvalte økosystemer bærekraftig for mennesker og natur. Imidlertid er det forskjellige måter som økosystemtjenester kan verdsettes på tvers av biofysiske, sosiokulturelle og monetære verdidomener, og disse verdiene samhandler innenfor og på tvers av domener. For å verdsette økosystemtjenester fullt ut er det behov for ikke bare å utvikle verdsettingsmetoder på tvers av alle tre domenene, men også måter å integrere på tvers av dem. Økosystemtjenester er ikke jevnt fordelt, og deres verdier er forskjellige i rom på grunn av ulike sosiale og økologiske faktorer. For å administrere økosystemtjenester må vi derfor også se hvordan og hvorfor verdiene deres varierer på tvers av landskap. og vi må gjøre rede for det dynamiske forholdet mellom økosystemtjenester på tvers av verdidomener og sosial-økologiske kontekster. I denne oppgaven presenterer jeg fire artikler som tar for seg noen av disse utfordringene med økosystemtjenester innenfor konteksten av et UNESCO-biosfærereservat på Vestlandet.

Først kartla vi sosiokulturelle verdier for økosystemtjenester ved hjelp av en undersøkelse av geografiske informasjonssystemer (PPGIS) for offentlig deltakelse. Vi undersøkte hvordan sosiokulturelle verdier for økosystemtjenesteverdier varierer på tvers av et biosfærereservat, hvilke verdier som vanligvis forekommer sammen i *bunter*, og hvilke sosial-økologiske egenskaper som bestemmer fordelingen av disse buntene. Folk kartla hovedsakelig steder for friluftsliv, biologisk mangfold, landbruksprodukter og kulturarv, hovedsakelig i områder med høyere menneskelig befolkning. Vi identifiserte fem bunter som representerer koblede biokulturelle verdier for landbruk og kulturarv, friluftsliv og biologisk mangfold, og vill mat og mental velvære. Generelt var tilgjengelighet den viktigste faktoren som avgjorde fordelingen av buntene.

For det andre integrerte vi biofysiske verdier med sosiokulturelle verdier og kartla økosystemtjenester i biosfærereservatet. Vi undersøkte fordelingen av disse integrerte økosystemtjenesteverdiene over biosfærereservatsonene og deres bunter over to romlige

skalaer. Økosystemtjenestene samlet inn i tre distinkte sosial-økologiske systemarketyper som var like i distribusjon og relative økosystemtjenesteverdier på begge romlige skalaer. Buntene var også godt tilpasset relative økosystemtjenesteverdier i biosfærereservatsonene (kjerne, buffer og overgang), noe som indikerer at buntene fanger opp de sosialøkologiske systemene i sonene. Disse resultatene viser at det er viktig å vurdere sonenes sosialøkologiske kontekst for å gi tilstrekkelig kunnskap til å informere ledelsen.

For det tredje brukte vi en ny kombinasjon av PPGIS og sosiale nettverksdata for å kartlegge økosystemets samproduksjonsnettverk i biosfærereservatet. Vi identifiserte fire komponenter i økosystemets samproduksjonsnettverk som sosiokulturelle verdier, direkte ledelse, styring og forskning/kunnskapsproduksjon. Først kartla vi den relative oppmerksomheten ulike økosystemtjenester mottok fra disse samproduksjonskomponentene. Deretter kartla vi det sosiale nettverket for kommunikasjon om ulike økosystemtjenester blant samproduksjonskomponentene. Vi fant misforhold mellom ulike komponenter i samproduksjonsnettverket. Viktigere, vi identifiserte at kulturelle økosystemer ble høyt verdsatt, men får relativt mindre styring og særlig forskningsoppmerksomhet. Videre var de primære forvalterne av kulturelle økosystemtjenester også dårlig koblet i økosystemtjenestens samproduksjonssosiale nettverk. Resultatene viser viktigheten av å tenke på samproduksjon av økosystemtjenester som et *relasjonelt nettverk* og av å kartlegge hva som diskuteres av hvem.

Til slutt integrerte vi økologiske feltundersøkelser og PPGIS for å utforske (mis)matchen i biofysiske og sosiokulturelle verdier for økosystemtjenester i sammenheng med landforlatelse og skogplanting. Biofysiske verdier for økosystemtjenester var mer like på tvers av vegetasjonstyper, mens sosiokulturelle verdier generelt var høyest i åpen vegetasjon og uplantede skogtyper. Økosystemtjenesten med størst forskjell i biofysiske og sosiokulturelle verdier global klimaregulering, mens biologisk mangfold og landbruksprodukter var like på tvers av verdidomenene. Sosiokulturelle verdier var ikke jevnt fordelt på studiedeltakerne. Det var to distinkte grupper som representerte eldre bønder bosatt i regionen med høye verdier for å levere økosystemtjenester på den ene siden, og yngre kvinner som ikke er innbyggere som verdsetter regulering og vedlikehold av økosystemtjenester. Denne studien viser viktigheten av å vurdere ulike både ulike verdidomener og faktorene som påvirker disse verdiene i beslutninger om endring av arealbruk.

Nøkkelord: økosystemtjenester, offentlig deltakelse geografiske informasjonssystemer, kartlegging, biofysisk, sosiokulturelt, verdivurdering, biosfærereservat, sosialt nettverk, arealbruksendring, Mennesket og biosfæren-programmet

LIST OF PUBLICATIONS

Publications included in the thesis

Paper I: **Cusens, J.**, Barraclough, A. D., & Måren, I. E. (2022). Participatory mapping reveals biocultural and nature values in the shared landscape of a Nordic UNESCO Biosphere Reserve. *People and Nature*, *4*(2), 365-381. doi:https://doi.org/10.1002/pan3.10287

Paper II: **Cusens, J.**, Barraclough, A. D., & Måren, I. E. (*Accepted*) Integration matters: Combining socio-cultural and biophysical methods for mapping ecosystem service bundles. *Ambio*.

Paper III: Barraclough, A. D., **Cusens, J.**, & Måren, I. E. (2022). Mapping stakeholder networks for the co-production of multiple ecosystem services: A novel mixed-methods approach. *Ecosystem Services*. 56, 101461. doi:https://doi.org/10.1016/j.ecoser.2022.101461

Paper IV: **Cusens, J.**, Barraclough, A. D., & Måren I. E., Socio-cultural values and biophysical supply: How do afforestation and land abandonment impact multiple ecosystem services? Manuscript submitted to *Land Use Policy*.

Other publications not included in the thesis

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Paper I, II and III are open access and reprints are made available through their Creative Commons Attribution License (CC BY 4.0). Papers IV is provided as a preprint.

AUTHOR CONTRIBUTIONS

Contributions to the papers in this PhD have been classified using the CRediT (Contributor Roles Taxonomy).

Role	Paper I	Paper II	Paper III	Paper VI
Conceptualization	JC, ADB, IEM	JC	ADB, JC	JC, ADB, IEM
Formal analysis	JC	JC	ADB	JC
Funding acquisition	IEM	IEM	IEM	IEM, JC
Investigation	JC, ADB	JC, ADB	ADB, JC	JC, ADB, IEM, TIS
Methodology	JC, ADB, IEM	JC	ADB, JC	JC, ADB, IEM, AWS
Project administration	JC, ADB, IEM	JC, IEM	ADB	JC, IEM
Software	JC	JC	ADB	JC
Supervision	IEM, ADB	IEM, ADB	IEM, ADB	IEM, ADB
Visualization	JC	JC	ADB, JC	JC
Writing - original draft	JC	JC	ADB	JC
Writing - review & editing	ADB, IEM, AWS	ADB, IEM	JC, IEM	ADB, IEM
Corresponding author	JC	JC	ADB	JC

JC = Jarrod Cusens[1,2], ADB = Alícia D. Barraclough[1,2,3], IEM = Inger Elisabeth Måren[1,2,3], AWS = Alistair William Seddon[1,4], TIS = Technicians, interns and students[5]

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4. Bjerknes Center for Climate Change Research, Bergen, Norway
5. Technicians, interns and students that assisted with the field survey in Paper IV were Linn Voldstad, Sebastian Måren, Sebastian Kvalsøy, Luise Stadler, Iselin Nygård, Morgane Demeaux and Klaartje Leemans.

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INTRODUCTION

It is difficult, sometimes even impossible, to value what cannot be named or described, and so the task of naming and describing is an essential one in any revolt against the status quo of capitalism and consumerism. Ultimately the destruction of the Earth is due in part, perhaps in large part, to a failure of the imagination or to its eclipse by systems of accounting that can't count what matters.

– (Solnit, 2015, pp. 97-98)

Human influence on the global biogeochemical system is so significant that it is argued that we should mark this influence by establishing the Anthropocene, an entirely new geological epoch (Steffen, Grinevald, Crutzen, & McNeill, 2011). The ongoing pressure on nature means we have now transgressed five of the environmental planetary boundaries and Earth's capacity to sustain life is in decline (Persson et al., 2022; Steffen et al., 2015). This crisis is nothing new: Rachel Carson catapulted it into the public discourse almost 60 years ago (Carson, 1964). Yet, despite early warnings (Meadows, Meadows, Randers, & Behrens III, 1972), biodiversity continues to be lost and ecosystems continue to be degraded with troubling consequences for nature's ability to support human wellbeing (IPBES, 2019).

Ecosystem services

The term ecosystem services was first introduced in the 1970s to put a focus on the importance of biodiversity for human wellbeing (Ehrlich & Ehrlich, 1981; Westman, 1977). The intention was to secure public interest and support in biodiversity conservation by highlighting our reliance on nature (Gómez-Baggethun, de Groot, Lomas, & Montes, 2010). Ecosystem services is now a 'household name' across many scientific disciplines and reaches beyond the academic boundary and on to the political agenda. Several global initiatives including the Millennium Ecosystem Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and the more recent and widely publicised Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) have helped ecosystem services gain momentum and the attention of academics and governments alike. But what exactly are ecosystem services? There is some variation in the specific definition of what ecosystem services are. For example, the MA defines ecosystem services as "the benefits people obtain from ecosystems" (MA, 2005, p. 40), while TEEB uses the "direct and indirect contributions of ecosystems to human well-being" (TEEB, 2010, p. 33).The latter definition from TEEB is also similarly adopted by the Common International Classification of Ecosystem Services (CICES) as "the contributions that ecosystems (i.e. living systems) make to human well-being" (Haines-Young & Potschin, 2018, p. 3). In addition to ecosystem services, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have introduced an additional term – nature's contributions to people – as "all the 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). Despite the variation in specifics within the definitions, fundamentally, however, it is understood that ecosystems services (and nature's contributions to people) are the contributions and benefits that people derive from ecosystems and nature (e.g., Díaz et al., 2018; Kadykalo et al., 2019; Maes, Burkhard, & Geneletti, 2018; Potschin & Haines-Young, 2016).

Box 1. A note on my use of *ecosystem services*

In this thesis I have used the term *ecosystem services*. In doing so I still acknowledge the debate surrounding the terms 'ecosystem services' and 'nature's contributions to people' (e.g., Díaz et al., 2018; Kadykalo et al., 2019; Maes et al, 2018; Kenter, 2018, Peterson et al., 2019, Braat, 2018). I use ecosystem services for three main reasons:

1. The framing of my work follows the recent ecosystem services literature and allows space for value pluralism and considers more than intrumental values alone (e.g., Jacobs et al., 2016, Maes et al., 2018)
2. Ecosystem services as a term already has a place in government and policy documents. I believe there is a risk of confusion by using a new term in work that is placed in a policy and planning context (e.g., Peterson et al., 2019) so this choice is pragmatic.
3. Three of the four papers in this thesis approach ecosystem services from an *ecosystem* perspective. That is, I have either modelled or directly measured the benefits that people received under the explicit assumption, and subsequently show emiprically, that different ecosystems provide different benefits and/or at different levels.

continued below…

Box 1. continued…

I have generally used the Common International Classification of Ecosystem Services (CICES) definition for ecosystem services and associated typology (v 5.1). This typology recognises three *sections* of ecosystem services (Haines-Young & Potschin, 2018):

1. Regulating and maintenance: "the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents"
2. Provisioning: nutritional, non-nutritional material and energetic outputs from living systems as well as abiotic outputs (including water)
3. Cultural: the non-material, and normally non-rival and non-consumptive, outputs of ecosystems (biotic and abiotic) that affect physical and mental states of people

I again acknowledge the existence of other major ecosystem service classification systems such as MA, TEEB and NCP, but have chosen CICES for pragmatic reasons.

The nature of ecosystem services lends itself to bring together a wide range of disciplines across the ecological and social sciences and has been identified as a *bridging concept* able to bridge multiple disciplines and fields of practice (Baggio, Brown, & Hellebrandt, 2015; Braat & de Groot, 2012; Malmborg, Enfors-Kautsky, Queiroz, Norström, & Schultz, 2021). However, it is important to emphasise that, ecosystem services in general are not simply 'gifts' from nature to people but are emergent properties of social-ecological systems coproduced by people and nature (Reyers et al., 2013; Spangenberg, Görg, et al., 2014). For example, trees are 'made' of timber that grow in 'nature'. But timber production requires several steps of intervention from us, such as planting and harvesting, both of which require technology and infrastructure like access roads. Ecosystem services can therefore be viewed as a link between social and ecological systems (Figure 1) (Díaz et al., 2015; Potschin & Haines-Young, 2016; Spangenberg, von Haaren, & Settele, 2014). This co-production relationship can be seen if we view ecosystem services through the cascade framework (Potschin & Haines-Young, 2011) that recognises a flow from the ecological system – the supply side – through to the social system – the demand side (Figure 1). The ecological and social system can be valued in biophysical terms, and monetary and socio-cultural terms respectively. The values measured or assigned in the value-domains can be used to inform governance of ecosystem services through policy actions to enhance and/or protect their supply (Figure 1).

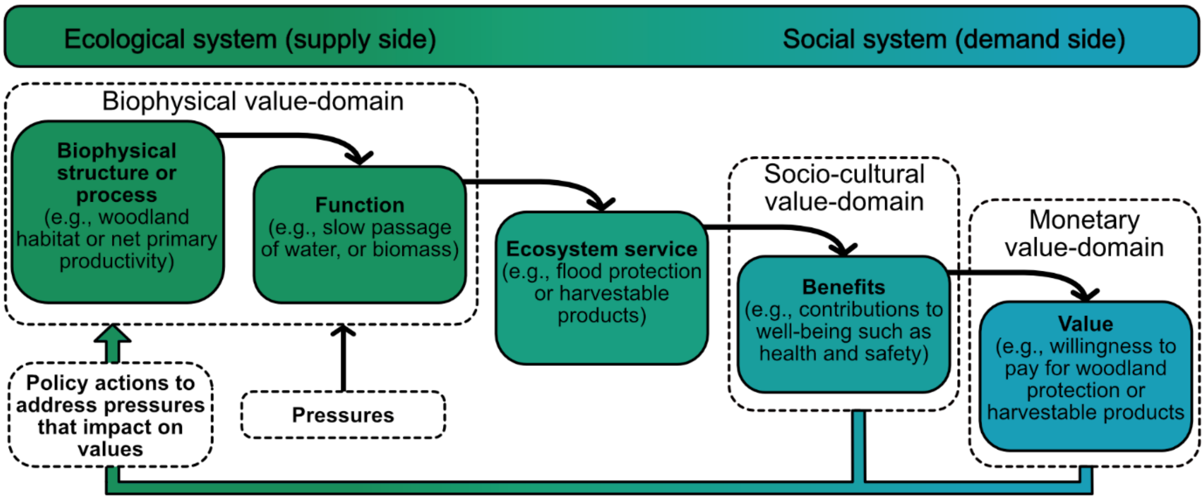

Figure 1. A representation of the ecosystem services 'cascade model' to illustrate how ecosystem services bridge the ecological and social systems, identifying the supply-demand relationship, the three value domains and the feedback of values on policy actions to manage pressures that impact ecosystem services supply. Inspired by Potschin and Haines-Young (2011), Spangenberg, von Haaren, et al. (2014) and Martín-López, Gómez-Baggethun, García-Llorente, and Montes (2014).

The ecosystem services bridge between social and ecological systems is further emphasised by recognising that ecological processes and functions are only ecosystem services if they have human beneficiaries (Spangenberg, Görg, et al., 2014). Thus, one of the goals of ecosystem services research has been to find ways of valuing the worth of the services that ecosystems provide. Valuation can focus on either the supply side of the ecosystem services cascade (biophysical values), or the demand side (socio-cultural and monetary values) (Figure 1). Among the three, monetary valuation has been the most prominent means for ‘demonstrating’ nature’s worth in an attempt to incentivise nature conservation (Chan & Satterfield, 2020; Martín-López et al., 2019; Schutter & Hicks, 2021). In 1997 several prominent scientists took up the mantle to establish the global economic worth of ecosystem services and published a now seminal paper arguing that, at the very least, the services that nature provides are worth twice that of global gross national product (Costanza et al., 1997). The purpose of that study was to address the failure of Neoclassical economics to recognise the contribution that nature makes to the economy. It was argued that by accounting for the monetary value of ecosystems, nature can be incorporated into economic decisions. It should therefore be possible to undertake economic cost-benefit analyses for developments that impact on ecosystem services and hence our well-being. For example, the cost of managing flood waters with engineered infrastructure might outweigh the cost of draining and infilling a wetland for a development if the wetland already performs that service (Bradbury et al., 2021).

Box 2. A note on *values* and *valuation*

In the context of ecosystem services values are the importance, worth or usefulness that people have for or place on nature and/or ecosystems. Valuation is the process of assessing how important or useful nature and/or ecosystem are at providing particular ecosystem services. Valuation occurs in three so-called value domains: (i) biophysical (or ecological), (ii) socio-cultural and (iii) monetary (e.g., Gómez-Baggethun, Barton, Berry, Dunford, & Harrison, 2016).

i. *Biophysical (ecological) values*: The importance of natural entities to perform functions that contribute to human wellbeing measured in biophysical terms.
ii. *Socio-cultural values*: The importance people, as individuals or as a group, assign to nature and/or ecosystems.
iii. *Monetary values*: Market values and/or the cost of replacement of natural entities if they are degraded or lost.

Unsurprisingly monetary valuations of nature are not without controversy, and criticisms abound in the academic and public discourse (Gómez-Baggethun et al., 2010; Schröter, van der Zanden, et al., 2014). Some have raised concerns about the commodification of nature and that monetary valuation of nature will lead to more, not less exploitation of nature (Fairhead, Leach, & Scoones, 2012; Gómez-Baggethun & Ruiz-Pérez, 2011; Raymond et al., 2013). In the public discourse, the well-known journalist and environmental activist George Monbiot has passionately attacked ecosystem services in *The Guardian* with concern of nature commodification (Monbiot, 2014). Reponses from prominent researchers in the ecosystem services field, including those that undertook the first global estimate of the economic value of ecosystem services (Costanza et al., 1997), have clearly stated that the intention of their work is not to drive the commodification of nature. Instead they argue that "[ecosystem] services must be (and are being) valued, and we need new, common asset institutions to better take these values into account" (Costanza et al., 2014, p. 152). In this, they are arguing that unless we can find robust ways to include nature in economic systems the services provided by nature will remain so-called *positive externalities*. Likewise, any negative effects on nature due to economic activities will remain externalities that need not be accounted for.

Multiple values and mixed-methods

While monetary valuation is an important tool in instances where the ecosystem service has a clear monetary value (e.g., timber production), it is by far not the only means of valuation. There are many instances where we either cannot put monetary values on something, or where it is inappropriate. For example, cultural ecosystem services (e.g., outdoor recreation, spiritual inspiration, scientific knowledge) are not tangible objects and can be viewed as collective goods that are more valuable for a group than for individuals. Thus, putting a price on cultural ecosystem services is generally inappropriate. People value nature and the contributions that nature makes to their quality of life in diverse ways shaped by their worldviews stemming from cultural backgrounds, knowledge systems (e.g., scientific, Indigenous) and languages (Anderson et al., 2022; Gould, Pai, Muraca, & Chan, 2019; Pascual et al., 2017). This value pluralism can be a source of conflict when certain values are prioritised over others in environmental decision making. Most commonly, monetary instrumental values (as a means to an end) take precedence over relational (relations and responsibilities among people, and between people and nature) and intrinsic (as an end in itself) values which has arguably led to declines in nature and ecosystem services (Anderson et al., 2022). Thus, it is not valuation itself that is a problem, but rather the types of values that are prioritised. So how do we go about representing values that we can't put a price on?

The need to explore alternative valuation methods for ecosystem services has gained traction in the literature over the last two decades (Chan & Satterfield, 2020; Martín-López et al., 2019). This valuation work can be done from strict single disciplinary or multidisciplinary approach or in more integrated interdisciplinary or transdisciplinary ways (see Figure 2 for a conceptual representation of these different -plinarities). The complexity of our multiple values for nature and ecosystem services suggested that the science aimed at solving these problems needs to employ a diversity of disciplines spanning not only scientific, but also traditional and Indigenous knowledge systems (IPBES, 2022). Indeed, there has been a shift in the methodologies in ecosystem services research in the past 15 years from largely single discipline biophysical and economic methods towards a higher proportion of pluralistic and socio-cultural methods (Martín-López et al., 2019; Schutter & Hicks, 2021). This is especially true for cultural ecosystem services which have tended to lag behind other categories of ecosystem services in valuation studies (Daniel et al., 2012; Fagerholm et al., 2019). Very recently, the IPBES 'Values Assessment' identified four *valuation method families* comprising (i) 'nature-based', (ii) 'statement-based', (iii) 'behaviour-based' and (vi) 'integrated' (IPBES, 2022). Critically, they report that integrated methods are the least used of the four method families in nature valuation. Thus, it is important to develop more integrated ways that include non-monetary approaches for valuing nature and the services provided by nature (Jacobs et al., 2016).

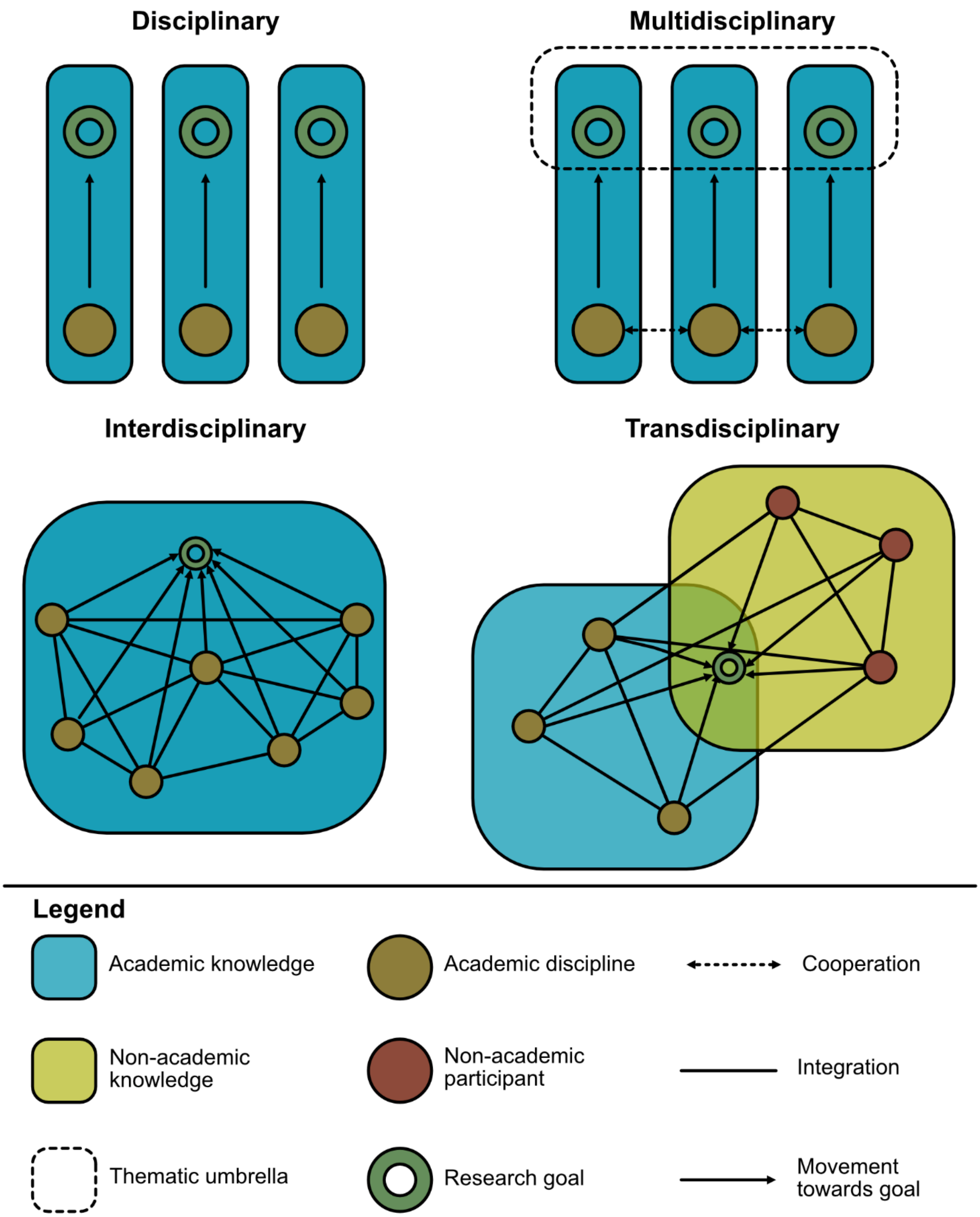

Figure 2. Graphical summary of the organisation of different -plinarities. Adapted from Tress, Tress, and Fry (2005).

Mapping ecosystem services

For ecosystem services to have a place in informing sustainable land use planning we need to know how ecosystem services vary quantitatively and spatially across different social ecological contexts (Cowling et al., 2008; Schröter, Barton, Remme, & Hein, 2014). This can be achieved through ecosystem service mapping which is in itself a large and rapidly expanding field with many different approaches and methods being developed (Burkhard & Maes, 2017). Naturally the choice of method will reflect the purpose of the mapping exercise as well as the availability of data, resources, and skills. But, there are other considerations that are important such as those related to stakeholder input, communication or participation in decision support (Harrison et al., 2018). Parallel to the field of ecosystem services in general, mapping has to date had a strong focus on biophysical values of provisioning and regulating and maintenance ecosystem services (Scholte, van Teeffelen, & Verburg, 2015). Biophysical approaches have contributed substantially to the understanding of the spatial distributions and interactions between ecosystem services, particularly provisioning, and regulating and maintenance ecosystem services (Chan & Satterfield, 2020). These biophysical methods link biological and physical attributes of the landscape to ecosystem services supply with varying degrees of complexity from simple proxy-based approaches assigning ecosystem services values to land-use/land-cover types, to more complex process-based models that incorporate a diversity of parameters such as geochemistry, climate and biotic characteristics like plant traits (reviewed by Lavorel et al., 2017). However, biophysical methods have been somewhat limited in their capacity to map cultural ecosystem services and are lacking in their ability to capture socio-cultural values of ecosystem services (Brown & Fagerholm, 2015; Chan & Satterfield, 2020).

There are several key methods to assess socio-cultural values[1] for ecosystem services including spatially explicit and non-spatial methods. Among the spatially explicit approaches Public Participation Geographic Information Systems (PPGIS) surveys and photo-series analysis from georeferenced social media are two prominent methods that are widely used (Brown & Fagerholm, 2015; Ghermandi & Sinclair, 2019; Muñoz, Hausner, Runge, Brown, & Daigle, 2020). Photo-series analysis relies on data that already exists, thus if people have not uploaded photos to a particular platform (e.g., *Flickr*) in the region of interest its use is limited. Further, additional data such as

[1] Social-cultural values are defined by by Scholte, van Teeffelen, and Verburg (2015, p. 68) as "the importance people, as individuals or as a group, assign to (bundles of) ESs".

demographics are not typically available and thus cannot be further analysed beyond spatial distributions of ecosystem services. An additional challenge is the need to analyse the content of photos and classify each photo by the ecosystem service it represents. PPGIS on the other hand is deliberative and requires survey participants to actively mark places on a map. Importantly, PPGIS surveys allow for additional survey questions that can be used to further analyse data such as socio-demographic information on participants.

Ecosystem service bundles

Landscapes provide different ecosystem services, or sets of ecosystem services, depending on their configuration such as the areal extent of the ecosystems, the geological landforms, and type and intensity of human intervention within them (Bennett, Peterson, & Gordon, 2009). Ecosystem service bundles–"sets of ecosystem services that repeatedly appear together across space or time" (Raudsepp-Hearne, Peterson, & Bennett, 2010, p. 5242) are widely used to assess the multifunctionality of landscapes and/or ecosystems (e.g., Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Turner, Odgaard, Bøcher, Dalgaard, & Svenning, 2014), although it has been pointed out that bundles are not synonymous with multifunctionality (Saidi & Spray, 2018). In a review (Meacham et al., 2022) identified five benefits of using ecosystem service bundle analyses related to (1) simplifying analysis, (2) simplifying management, (3) developing practical social-ecological theory, (4) filling data gaps, and (5) acting as a bridging tool. In addition, ecosystem service bundles can assist in identifying social-ecological system archetypes within a landscape (Hamann, Biggs, & Reyers, 2015). Since ecosystem services are typically coproduced by people and nature (Spangenberg, Görg, et al., 2014), ecosystem service bundles can be recognised as distinct social-ecological systems that have emerged though complex interactions and feedbacks between social and ecological systems landscape (Folke et al., 2010; Hamann et al., 2015; Reyers et al., 2013). These social-ecological system archetypes can provide important information to guide conservation planning and management, particularly in light of modern framing of conservation as 'People and Nature' (Mace, 2014)a(cf. Mace, 2014).

UNESCO Biosphere Reserves

In 1971 The United Nations Educational, Scientific and Cultural Organization (UNESCO) launched the Man and Biosphere (MAB) programme with the aim "to establish a scientific basis for improvement of relationships between people and their environments" (UNESCO, 2017, p. 12). In 1976 MAB began establishing a world network of Biosphere Reserves (BRs) that, as of July 2022 comprises 738 sites spread across 134 countries. Biosphere Reserves are examples of social-ecological systems spanning numerous biomes and ecosystems that have been described broadly as learning sites, living laboratories or model regions for sustainable development (Kratzer, 2018; Schultz et al., 2018; Starger, 2016). These BRs form the basis for the implementation of the updated MAB Strategy (2015-2025) and the Lima Action Plan (2016-2025) (UNESCO, 2017). The Lima Action Plan clearly highlights BRs as sites that are sources and stewards of ecosystem services and that contribute to achieving the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015).

The Seville Strategy (UNESCO, 1996) gives BRs three primary interconnected functions: (1) conservation, (2) sustainable development and (3) logistic support for project, education, research and monitoring (Figure 3). Prior to The Seville Strategy 'first generation' BRs designated between 1974 and 1995 had a strong focus on nature conservation and scientific research (Ishwaran, Persic, & Tri, 2008; Reed, 2020). Since then, BRs have undergone an evolution and shifted focus in line with The Seville Strategy (Reed, 2020; Winkler, 2019). Importantly, 'conservation' referred to in function one comprises not only biodiversity conservation, but also biocultural diversity conservation. Biocultural diversity conservation is a primary aim of BRs designated since 1995, defined by Maffi (2005, p. 602) as the "diversity of life in all its manifestations—biological, cultural, and linguistic—which are interrelated within a complex socio-ecological adaptive system". This consideration of 'People and Nature' in the biocultural paradigm of BRs places them squarely within the contemporary framing of conservation (cf. Mace, 2014).

The three functions of BRs are implemented through a system of zonation, comprising core, buffer, and transition/development zones. Zonation was originally conceived of as a ‘fried egg’ with core zones surrounded by buffer zones which are all surrounded by the transition zone (Figure 3) (Reed, 2020). Core zones should comprise legally protected areas dedicated to conservation of biodiversity and low impact activities. Buffers zones typically surround the core zones and should be used for ecologically compatible collaborative activities. The transition zone comprises the rest of the biosphere reserve which includes various human activities compatible with sustainable development. In recent years, zonation design has become more flexible and is interpreted in the local context and does not always strictly follow the ‘fried egg’ format.

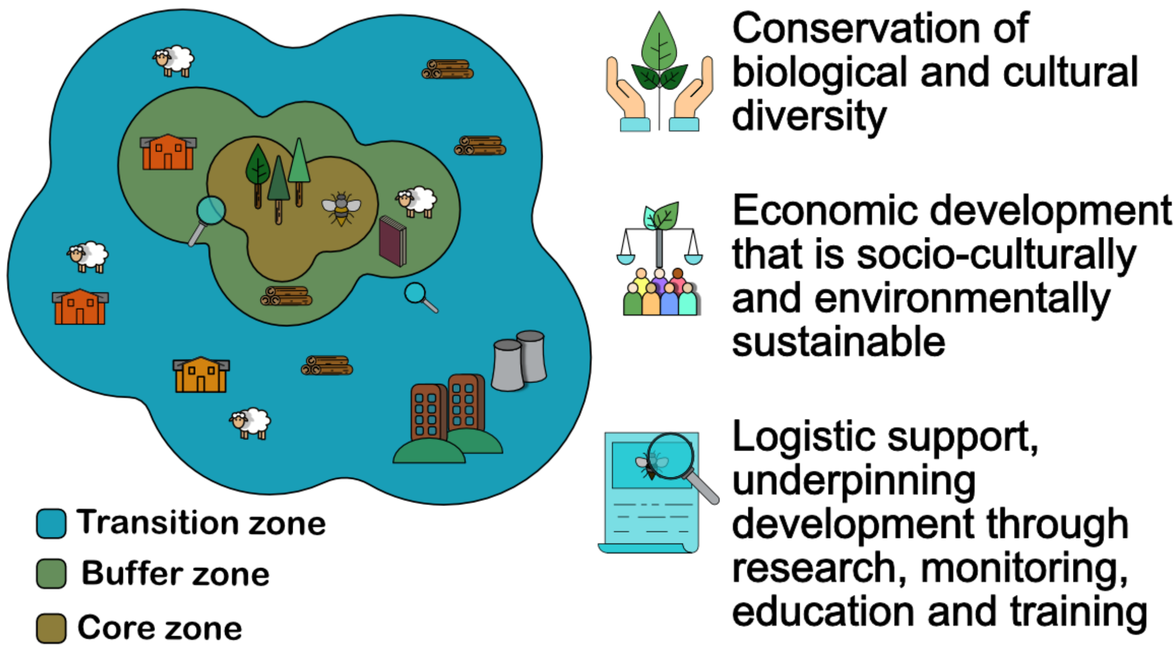

Figure 3. Conceptual representation of the UNESCO Biosphere Reserve zonation and the three functions of Biosphere Reserves. Adapted from https://en.unesco.org/biosphere/

AIM AND OBJECTIVES

The aim of this thesis was "to map and document selected ecosystem services, and knowledge and perceptions of ecosystems and ecosystem services related to shifting population pressures and land-use processes, and to create citizen science projects to facilitate co-production of knowledge in Nordhordland". The work is embedded within a project funded by the Research Council of Norway (grant no. 280299, *TRADMOD: From traditional resource use to modern industrial production: holistic management in Western Norway*). My work takes inspiration from 'Work package 1 Land-use change: effects on ecosystems, ecosystem services, and cultural environments'. The objectives to achieve the aim of this thesis were (i) studying the spatial distribution of socio-cultural values for ecosystem services with a focus on the bundling and variation in ecosystem service values among the biosphere reserve zones (**Paper I**); (ii) mapping social-ecological system archetypes in the biosphere reserve by integrating socio-cultural methods for cultural ecosystem services with biophysical methods for provisioning, and regulating and maintenance ecosystem services (**Paper II**); (iii) mapping social networks of ecosystem service governance, management and use to identify the social-ecological (mis)match of ecosystem services coproduction in the biosphere reserve (**Paper III**); and (vi) a novel multi-method approach to explore potential impacts of afforestation and agricultural abandonment on socio-cultural values and biophysical supply of ecosystem services in western Norway (**Paper IV**).

Nordhordland Biosphere Reserve as a case study region

All the work presented in this thesis is undertaken within the Nordhordland UNESCO Biosphere Reserve. Nordhordland Biosphere Reserve was chosen for a combination of reasons. Firstly, the region is practically located within a half-an-hour drive from Bergen where I was located. Second, there is a long-standing relationship between various actors and researchers at Department of Biological Sciences where I am based. Prominently, work in the coastal heathlands of the region by Peter Emil Kaland and others stretches back to the 1970s. More recently, my supervisor, Inger Måren, conducted her PhD research within the heathlands of the region.

The following poem by Gunnar Staalesen, a Bergen based writer, captures the essence of Nordhordland, described by Staalesen as "Norway in miniature" (Kaland et al., 2018). A less romantic but nonetheless important contextual description of Nordhordland Biosphere Reserve follows below. Interestingly, in his romantic version Gunnar Staalsen does not mention the climate, whereas I do. I leave it to the reader to draw their own conclusions about that omission.

Fra de ytterste skjær
der havdønningene slår som klodens egne pulsslag innover svabergene
over lyngheier og sund, innmark og utmark, knauser og koller
helt inn til der landskapet stiger steilt mot fjellheimen og støl ligger bak støl
mot himmelranden, er Nordhordland et lite stykke Norge i miniatyr.
Selv om hele landsdelen fra Fedje til Stølsheimen
var løsnet fra kysten og kommet i drift
hadde den likevel hatt det meste av det landet har å by på - med seg.

From the outermost skerry,
where the ocean swell washes like the planet's own heartbeats onto the rocks,
across heaths and straits, infields and outfields, knolls and hillocks
all the way to where the landscape climbs steeply up towards the mountains,
and farm stands behind farm all the way to the sky,
Nordhordland is Norway in miniature.

Even if the whole region from Fedje to Stølsheimen was torn from the coast and set adrift, it would nevertheless contain most of what this country has to offer.

Nordhordland Biosphere Reserve is located on the west coast of Norway covering *c*.6,698 km^2 stretching from the open Atlantic Ocean and coastal flats in the west, up to the mountains in the east reaching up to 1,313 masl at Kleivfjellet (Figure 4). Extensive fjord systems comprise an important component of Nordhordland Biosphere Reserve, including Sognefjorden; Europe's longest, and Norway's longest and deepest fjord (205 kilometres long and 1,308 metres maximum depth). Terrestrial landcovers with the greatest areal extents are open and sparse vegetation and forest along with marine ecosystems in the fjords and open ocean (Figure 4b).

The climate is a wet-temperate oceanic climate with mean annual precipitation of 2,400 mm and a strong west-east gradient from coast to the mountains; coastal areas receive 1,300 mm precipitation per year while the upland areas receive 3,000 mm. Mean temperature of the warmest and coldest months are 13.0–14.5°C and 3.0–-3.0°C, respectively in the coastal areas. Temperature variation on the coast is modest with the difference between the warmest and coldest months being 11°C while inland the difference is greater at 16°C.

Historically people in the area were farmer-fishers who made effective use of the natural resources at hand including fish, livestock grazing in the mountains and coastal heathlands that they managed for such use. Much of the migration in recent times can be related to industrial growth in the area from Mongstad oil refinery and related petrochemical industry. Today employment is predominantly provided by public services while economic activity is dominated by the petroleum industry centred at Mongstad comprising Norway's largest oil refinery and other petroleum businesses. The region is an important provider of hydroelectricity at the national level with production centred in Modalen and Masfjorden municipalities. Although agriculture and fishing are not major economic players, they are nonetheless culturally significant. Aquaculture and fisheries are important industries with large pelagic fish stock and salmon aquaculture which is projected to expand in the future.

There is evidence of settlement from more than 10,000 years ago and the population has been steadily increasing since the 1980s to 2020 (Statistics Norway, 2020). At present Nordhordland Biosphere Reserve comprises nine municipalities that are contained entirely with its boundaries, with a further five partially within the boundaries (Figure 4a). The permanent human population of the nine main municipalities is *c*.54,000 concentrated in the low-lying southwestern coastal areas (Figure 4a) along with an additional c.15,000 seasonal residents comprising predominantly holiday-home owners (Kaland et al., 2018). A further *c*.332,000 people live in the additional five municipalities, concentrated primarily in Bergen municipality (*c*.281,190 people).

The zonation of Nordhordland Biosphere Reserve comprises four localities with a core and buffer zone associated with each of those localities (Figure 4) (Kaland et al., 2018). The zones represent all the major land- and seascapes in Nordhordland Biosphere Reserve, including the coast and outer archipelago (Lurefjorden), the fjord landscape (Osterfjorden and Loneelvi River) and the mountain landscape (Stølsheimen; Figure 4). Each locality has its own unique characteristics encompassing the breadth of biocultural diversity found in Nordhordland Biosphere Reserve including cultural heritage monuments and upland summer farms at Stølsheimen, agricultural and cultural landscapes in the buffer zones of Loneelvi and Lurefjorden, and important biodiversity and research sites in the core areas of Lurefjorden and the Osterfjorden.

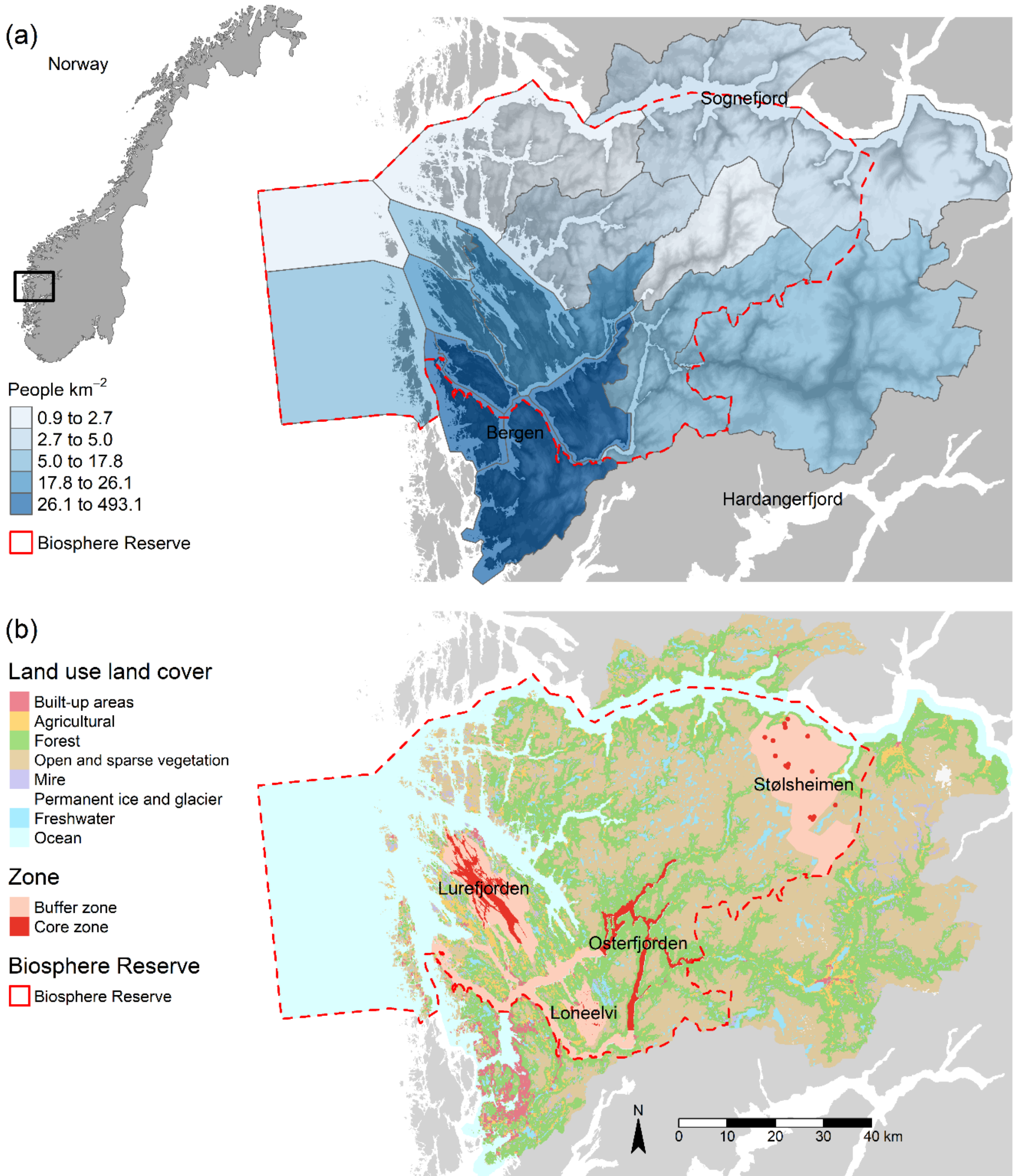

Figure 4. (a) Location and population densities of the municipalities, and (b) land use-land cover and the location of the different zones and in Nordhordland UNESCO Biosphere at the west coast of Norway.

Organisation of the four papers

This thesis is based on four papers that explore different methods from different disciplines for mapping and assessing ecosystem services. There are three main unifying threads that include: (1) the overarching theme of ecosystem services, (2) the social-ecological context of Nordhordland Biosphere Reserve, and (3) the methodological thread. All four papers used data collected with a public participation geographic information systems (PPGIS) survey in some way or another (Figure 5). The PPGIS data were used either alone (**Paper I**) or in combination with other data including biophysical models (**Paper II**), social network data (**Paper III**) and ecological field data (**Paper IV**) (Figure 5). In the following I give a brief summary of the data sources and methods used for each of the four papers.

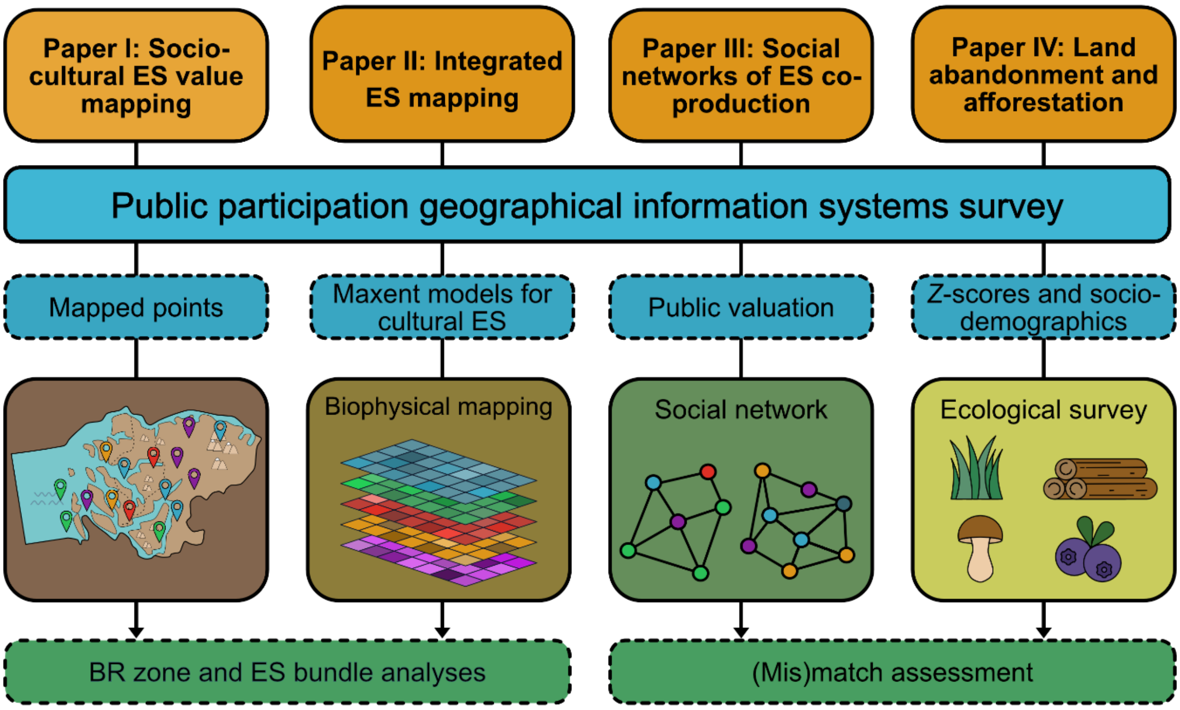

Figure 5. Conceptual diagram of the papers presented in this thesis including the common thread of public participation GIS and how it was treated in each paper, the additional data types included in the Papers II–IV, and broad overview of the types of analyses used in each paper.

Participatory mapping of ecosystem services (Paper I)

Paper I is based primarily on data collected with an online PPGIS survey. Participants were presented with a list of 12 ecosystem services and asked to map places within Nordhordland Biosphere Reserve where they perceive and value those ecosystem services. The survey questions were adapted from previously published PPGIS surveys (Fagerholm et al., 2016; Fagerholm et al., 2019; Garcia-Martin et al., 2017) and sought to capture spatial dimension of the use and subjective perceptions components of socio-cultural values for ecosystem services (cf. Scholte et al., 2015). Before releasing the survey, a workshop was held with local stakeholders to test the survey and to refine the ecosystem services typology. This was a critical step in the process and resulted in modification to both the typology of ecosystem services, and the wording of the ecosystem service statements, to make them locally relevant and understandable to non-expert participants in the study. Participants for the PPGIS survey were recruited in several ways including: (i) targeted email lists comprising local actors from organisations and institutions involved in resource management, local and regional government, agriculture, nature conservation, forestry and energy production; (ii) articles about the project and survey in one regional newspaper and two local newspapers (Figure 6); (iii) boosted social media adverts; and promotions on the Nordhordland Biosphere Reserve social media accounts, (iv) a series of public open sessions across public libraries and community halls in each municipality (Figure 7), and (v) snowballing.

Figure 6. A newspaper advertisement inviting local stakeholders to participate in the PPGIS survey.

Figure 7. Photos of workshops with participants in the different municipalities of Nordhordland Biosphere Reserve during the PPGIS survey campaign in February 2020.

The data collected in the PPGIS survey was analysed in four main ways. First, I used kernel density analysis to identify hotspots of all ecosystem services and the three categories of ecosystem services separately (i.e., provisioning, cultural, regulating & maintenance). This is a commonly employed method for hotspot detection in PPGIS studies (e.g., Alessa, Kliskey, & Brown, 2008; Hausner, Brown, & Lægreid, 2015). Secondly, I undertook an ecosystem services bundle analysis at a grid-cell scale to identify groups of repeatedly co-occurring ecosystem services value bundles (Raudsepp-Hearne et al., 2010). The approach was similar to that of Plieninger, Torralba, Hartel, and Fagerholm (2019) using hierarchical clustering on the principal components of gird-cell point-densities for each ecosystem service. Third, I used maximum entropy modelling to map the distribution of the bundles and to assess the importance of spatial landscape characteristics in determining their spatial distribution. Maximum entropy modelling method is used widely in ecology and biogeography for species distribution modelling and is increasingly used in modelling ecosystem service values collected with PPGIS surveys (Muñoz et al., 2020; Sherrouse, Clement, & Semmens, 2011; Sherrouse, Semmens, & Clement, 2014). Finally, I undertook a simple overlay analysis and counted the number of points mapped for each ecosystem service in the entire biosphere reserve, in the main aggregated transition, core and buffer zones, and then for each individual zone polygon.

Integrated mapping of ecosystem service bundles (Paper II)

In **Paper II** I used of a combination of data from the PPGIS survey to map six cultural ecosystem services and different spatial models to map three provisioning and five regulating and maintenance ecosystem services. For cultural ecosystem services I used an approach similar to Sherrouse et al. (2014) using maximum entropy modelling with 10 spatially explicit social-ecological landscape characteristics. For the other ecosystem services, I used several approaches including: (i) national statistics available at the municipality and/or regional level downscaled to a grid (e.g., fodder production); (ii) LULC proxy-based models (e.g., carbon storage); and (iii) process-based models (e.g., water regulation). All ecosystem services were mapped at a 250-metre grid scale.

The data were analysed in two main ways, both of which share similarities with **Paper I**. First, compared the provision of each ecosystem services among the biosphere reserve zones. Here I calculated the median values of grid-scale ecosystem services data (i) aggregated to the three main zones (i.e., transition, buffer, core) and (ii) to each individual zone. I tested for difference in the ecosystem service supply between zones in all ecosystem types, and within only terrestrial and only marine ecosystem types using used pairwise Wilcoxon rank sum tests. Second, I produced ecosystem service bundles at two spatial scales (i) using municipalities and (ii) grid cells as the spatial units. For the municipality scale I aggregated the grid scale data at the municipality scale. Bundles were produced following a similar methodology of many other studies using *k*-means clustering on the principal components of all ecosystem services (e.g., Malmborg et al., 2021; Quintas-Soriano et al., 2019; Raudsepp-Hearne et al., 2010; Saidi & Spray, 2018). I calculated the mean value for each ecosystem service in each bundle at both scales to compare the relative ecosystem service supply among bundles and across scales. I also used the relative proportion of different landcovers in each bundle to qualitatively describe the social-ecological characteristics of the bundles (Meacham, Queiroz, Norström, & Peterson, 2016; Rolo et al., 2021).

Social networks of ecosystem service co-production (Paper III)

The data for **Paper III** is based on data from the public value mapping from the PPGIS survey and an extension to that survey for individuals identified as key stakeholders involved in natural resource management in Nordhordland Biosphere Reserve. The analytical framing of **Paper III** views ecosystem service co-production as a network of stakeholders that interact with ecosystem in different ways. We defined four co-production relationships that stakeholders have with ecosystem services as (i) socio-cultural values, (ii) management, (iii) governance, and (iv) research and/or knowledge. Key stakeholders were identified based on a list of 10 self-selected roles within the biosphere reserve (Table 1). First, we looked for (mis)match between the four different types of co-production relationships with the different ecosystem services. For socio-cultural values we used the number of points mapped by the public for each ecosystem service, while for the other three co-production relationships we counted the number of key stakeholders that identified one of those relationships with the ecosystem services. Second, we explored the relationships each of the stakeholders had with the different ecosystem services. Finally, we constructed a social network by asking key stakeholders to identify which stakeholder classes they regularly communicated with and which ecosystem services they communicated about. We constructed an overall social network including all key stakeholders and all ecosystem services and three separate networks for each of the ecosystems service classes (provisioning, cultural and regulating and maintenance). In the overall network we identified two different community types based on (i) the structure of the social network and connections between stakeholders and (ii) the ecosystem services bundle they communicate about. In the ecosystem class networks we identified the community clusters based on measures of network structure.

Table 1. The 10 stakeholder classes and their definitions used in Paper III.

Stakeholder Class	**Description**
Farmers	Farming union representatives, individual part- and full-time farmers
Hunters and fishers	Hunting and fishing organization representatives and individual hunters and fishermen
Industry	Representatives of the aquaculture industry, oil industry, energy industry and forestry
Business	Consultants engaged in environmental monitoring and mapping, tourism businesses, gastronomy related businesses, small-scale timber and wood businesses

Stakeholder Class	Description
"Lag og foreiningar" (clubs and community groups)	Small (neighbourhood or local) community clubs, groups, and associations for local culture, environment, nature, or outdoor pursuits.
Organizations	Larger regional scale organizations and non-profits for the preservation of cultural landscapes, nature conservation, and cultural heritage
Local government	Local municipality heads of agriculture, forestry, landscape planning, culture and general coordination (in the case of very small municipalities)
National government	Coastal management, environment office
Regional government	Regional government representatives for nature management, agriculture, culture, education and general coordination.
Scientist/researcher	Researchers from higher education institutions and research centres working on environmental science, ecology, eco-economics and marine research
Other	Community members, landowners, and foragers

Land-use change impacts on socio-cultural and biophysical ecosystem service values (Paper IV)

Paper IV is based on two distinct forms of data collected from the (i) PPGIS survey and (ii) from ecological field surveys. For the field survey we selected 33 sites within Alver municipality (Figure 8), one of the nine municipalities in Nordhordland Biosphere Reserve, spread across four ecosystem types including (a) open semi-natural vegetation (hereafter open vegetation), and (b) three forest types; (i) natural mixed broadleaved forests dominated by birch (*Betula* spp.) (hereafter broadleaved forest) and (ii) coastal pine forests (*Pinus sylvestris*) (hereafter pine forest), and (iii) planted spruce forests (*Picea* spp.). At each site I collected data to calculate indicators for six different ecosystem services (Table 2, Figure 9). From the PPGIS survey we used socio-demographic data and points mapped for the six ecosystem services within one of the four ecosystem types.

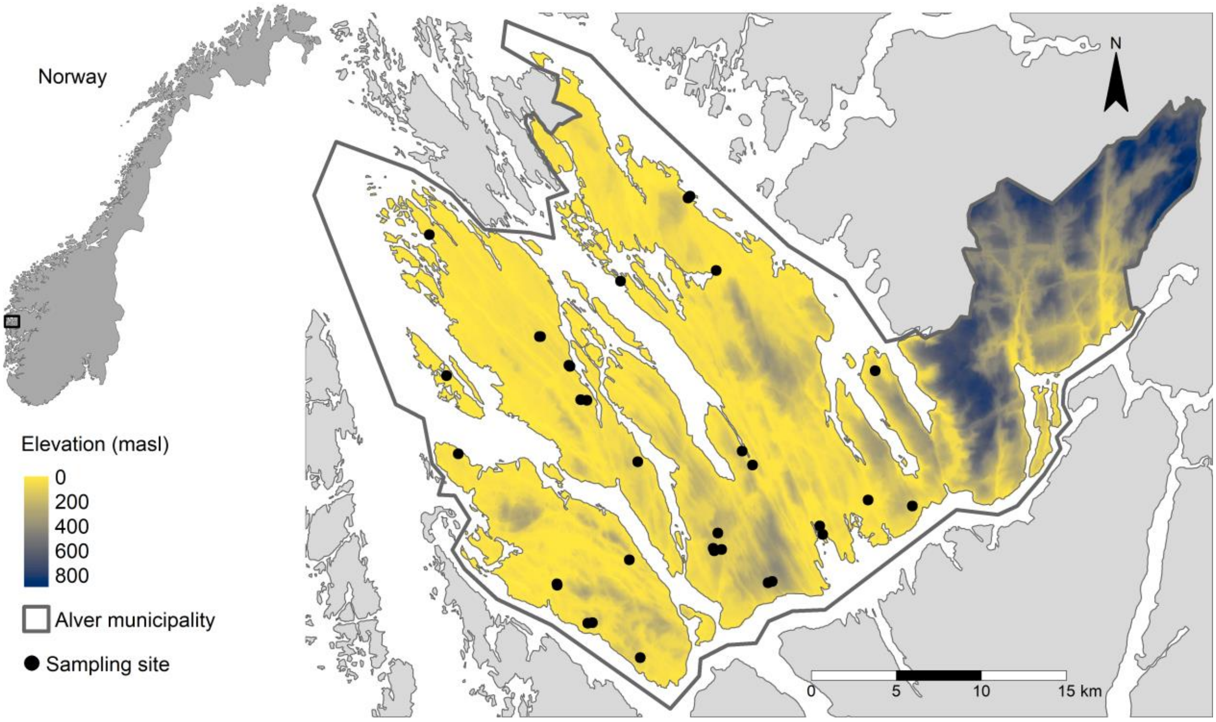

Figure 8. Location and elevation profile of the study area and the location of the 33 sampling sites.

Table 2. Summary of the different ecosystem services assessed, the biophysical indicators, units used to quantify them and sources for the indicators.

Ecosystem service	Biophysical indicator(s)	Units	Reference
Cultural			
Wild food[1]	Berries; mushrooms	kg/ha	Schulp, Thuiller, and Verburg (2014)
Aesthetics	Ratio of herbs to grasses; flower colour richness	%; flower colours/ha	Johansen, Taugourdeau, Hovstad, and Wehn (2019); Ford, Garbutt, Jones, and Jones (2012)
Provisioning			
Forage provision	Cover of graminoid species	%	Lavorel et al. (2011); Johansen et al. (2019)
Timber & firewood	Volume of timber	m3/ha	Haines-Young and Potschin (2018)
Regulating & maintenance			
Global climate regulation	Biomass carbon; soil carbon (loss on ignition)	ton/ha; %	Johansen et al. (2019); Haines-

Ecosystem service	Biophysical indicator(s)	Units	Reference
Habitat provision/biodiversity appreciation[2]	Species richness of vascular plants; standing dead wood	species/ha; m3/ha	Young and Potschin (2018) Gamfeldt et al. (2013); Gao, Nielsen, and Hedblom (2015)

1. Wild food is classified as a provisioning service in CICES. However, we have classified wild food as a cultural service, consistent with the socio-economic background of our study region (Reyes-García et al., 2015).
2. The biophysical indicator is classified as a regulating and maintenance in CICES but the socio-cultural value is conceptualised as a cultural services in the appreciation of biodiversity (Haines-Young & Potschin, 2018).

Figure 9. Photographs from field work associated with Paper IV.

We compared the difference in biophysical supply of ecosystem services in the different ecosystem types using pairwise Wilcox tests. Then we used pairwise correlation analysis evaluate trade-offs and synergies of the biophysical ecosystem service supply between pairs of ecosystems service indicators. To determine the socio-cultural values of the different ecosystem services we used *z*-scores to assess whether the number of points mapped for each ecosystem type were higher or lower than could be expected by chance

(Brown, Hausner, & Lægreid, 2015). We used Pearson's Chi-squared tests to test for the effect of socio-demographic factors and habitat type on the number of points mapped per ecosystem service by survey participants. In addition, we used Cramér's V to test for the strength of the association between the variables and the number of points mapped per ecosystem service (Fagerholm et al., 2019). We used multiple correspondence analysis to explore the association between the mapped socio-cultural values for ecosystem service in the different vegetation types, and socio-demographic characteristics of survey participants. Finally, we did a cross comparison of the biophysical supply values and socio-cultural values to look for matches or mismatches between these two value domains.

RESULTS AND FINDINGS

In this section I present the main results and findings of each paper along with a brief summary discussion of the results in context. More detailed results and discussion can be found in the full-length papers.

Participatory mapping of ecosystem services (Paper I)

Which ecosystem services and where?

Two clear findings in **Paper I** were (i) the predominance of places that people mapped for outdoor recreation, and cultural ecosystem services more generally (Figure 11), and (ii) the high density of points mapped in the more populated areas (see Figure 3 in **Paper I**). These are perhaps not the most surprising findings and are more like *confirmatory* results. The predominance of mapped places for outdoor recreation has been reported in other sites with similar socio-demographic contexts (e.g., Fagerholm et al., 2019). It is important to note too that outdoor life (*friluftliv*) is a fundamental part of the Norwegian cultural identity that is written into law though *Allemannsretten* (everyman's right/freedom to roam). Hotspots of mapping are also typically found close to where people live and can be attributed to (i) accessibility as an important determinant of the well-being benefits related to nature-based recreation (Ala-Hulkko, Kotavaara, Alahuhta, Helle, & Hjort, 2016), and (ii) geographic discounting – people choose to be close to the things they value on the one hand but prefer to be more distant from what they have an aversion to on the other (Brown & Kyttä, 2014).

Biosphere reserve zones

Mapped ecosystem service values in the transition zones were indistinguishable between the transition zone and the whole biosphere reserve (Figure 10). This can be explained relatively simply by the similar proportions of different land use/land cover types in the transition zone compared to the whole biosphere reserve. The difference between the zones is more revealing. The buffer zone and transition zones were similar, but the buffer zone had higher values for agricultural products and cultural heritage which are values that are closely linked in Nordhordland (see *Bundles of socio-cultural values* below for more on this). The core zone was the most distinct with many places mapped for hunting and fishing, and very few for agricultural products (Figure 10). The high number of points for fishing can be explained by the dominance of marine environments in the core zones. There was substantial variation in mapped values among specific zones with hunting and fishing evident in the marine zones, agricultural products in the lowland buffer zones and recreation in the upland zones (Figure 10). The lowland terrestrial buffer zones have proportionately higher agricultural land than the other zones which helps to explain the high agricultural values in these zones.

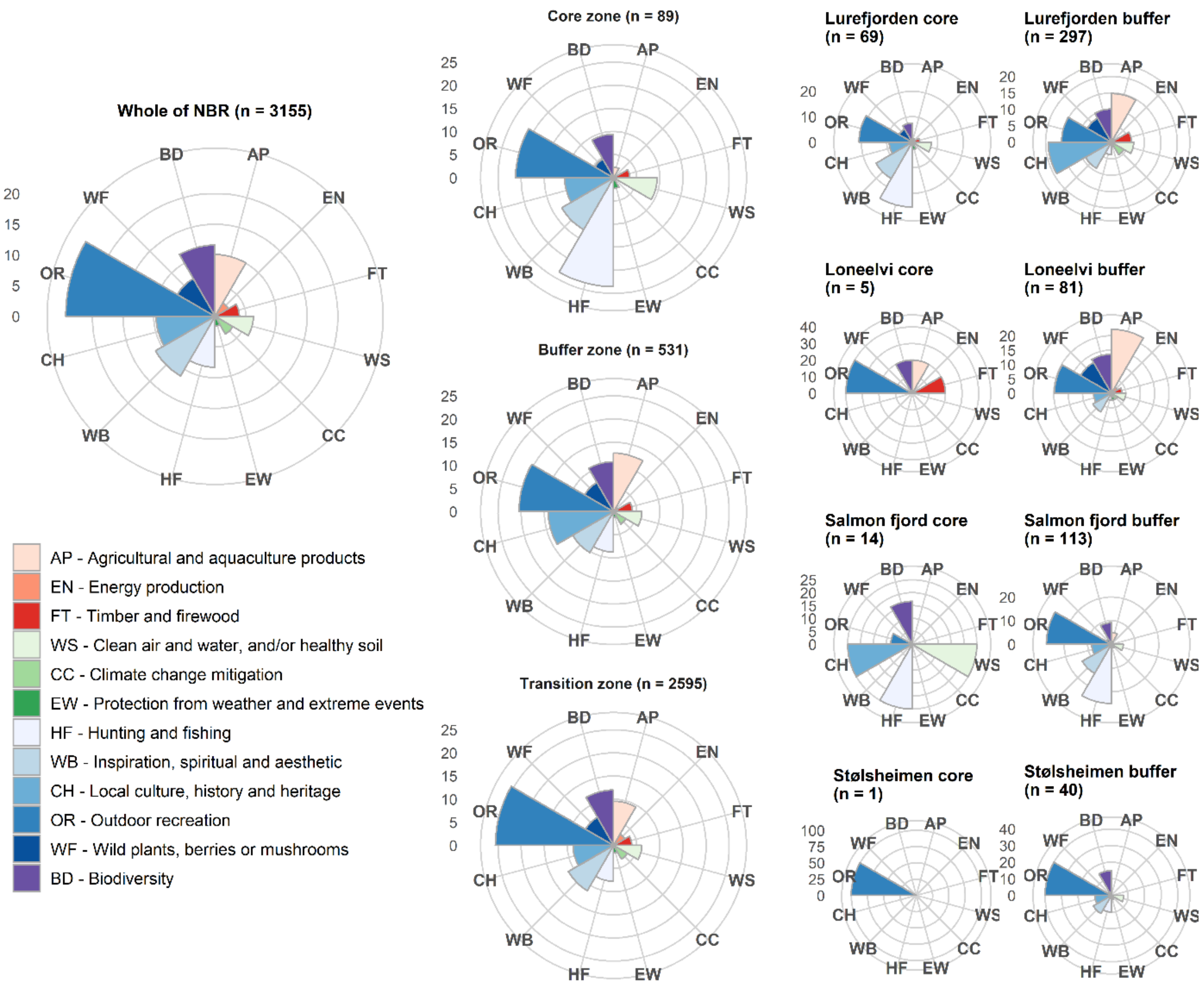

Figure 10. Proportion of points mapped for each ecosystem service value in the PPGIS survey in the whole of Nordhordland UNESCO Biosphere Reserve, the three biosphere zones, and the specific zones. Petals are the percentage of points mapped per ecosystem service value within each zone and represent differences in ecosystem service values within each petal diagram.

Bundles of socio-cultural values

The socio-cultural values formed five distinct spatial bundles (Figure 12). All bundles, aside from ‘multifunctional landscapes’ were dominated by one or two ecosystem services. The bundles were classified as: (1) ‘passive cultural values’, characterised by predominantly mental well-being and non-animal wild food values; (2) ‘multifunctional landscapes’, characterised by a relatively even spread of ecosystem services values but a higher proportion provisioning relative to other ecosystem service classes; (3) ‘cultural landscapes’, dominated by agriculture and cultural heritage values; (4) ‘active outdoor recreation’, characterised by dominance of outdoor recreation values, and to a lesser degree biodiversity values; and (5) ‘wild animal resources’, dominated by hunting and fishing. The bundles reveal some key linked places-based values. For example, the cooccurrence of agricultural values and cultural heritage values in areas with a high proportion of agricultural land is typical for societies with strong agrarian histories, including Nordhordland (Kaland et al., 2018; Olwig, 2007). Overall, accessibility in different forms was important for the distribution of the bundles. This includes distance from human infrastructure such as roads, hiking trails and buildings, as well as the terrain, elevation, and slope. This can be classified as a *confirmatory result* and is a common attribute in similar studies (e.g., Fagerholm et al., 2019; Plieninger et al., 2019) (See also *Which ecosystem services and where?* above). Land cover richness was important for some bundles and has strong ties to aesthetic appreciation values (Dramstad, Tveit, Fjellstad, & Fry, 2006) and multifunctionality (Kremen & Merenlender, 2018; Manning et al., 2018).

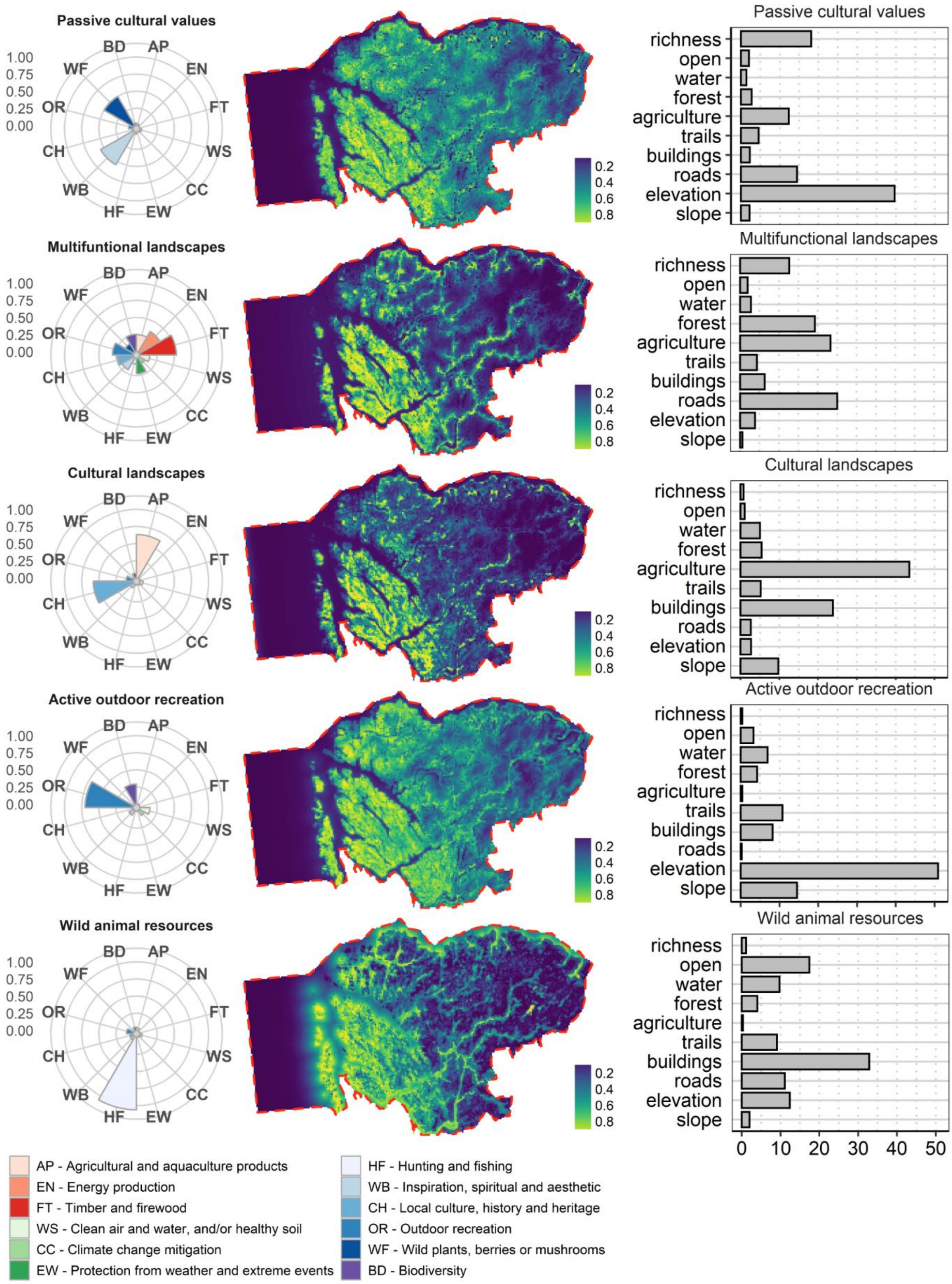

Figure 12. The relative socio-cultural values for ecosystem services in the five bundles, their probability distribution estimated with maximum entropy modelling, and the importance of each of the 10 landscape characteristics in determining the distribution of the bundles in Nordhordland UNESCO Biosphere Reserve.

Integrated mapping of ecosystem service bundles (Paper II)

Biosphere reserve zones

Relative values for ecosystem services were similar in the transition and buffer zones, while the core zone was distinct in supporting generally higher values for cultural ecosystem services, especially hunting and fishing (Figure 12a). The similarity of the transition and buffer zones and distinct core zone mirrors that of the purely socio-cultural values from **Paper I**. An important finding was the similarity of the lowland core and buffer zones, upland core and buffer zones and all of the marine zones (Figure 12b & c). Lowland terrestrial zones typically had high values for cultural ecosystem services, upland zones had highest values for regulating and maintenance ecosystem services while marine zones had high values for hunting and fishing and habitat quality (Figure 12b & c). This result is important when considering ecosystem service assessments across biosphere reserve zones. Typically, similar studies that have mapped ecosystem service values among the zones of biosphere reserves have aggregated all the core and buffer zones (e.g., Castillo-Eguskitza, Schmitz, Onaindia, & Rescia, 2019; Palliwoda et al., 2021). But most biosphere reserves do not comprise a single core or buffer zone, and zones of the same type may comprise different ecosystem types. This means that aggregate ecosystem services values across all core or buffer zones may fail to capture the idiosyncrasies in ecosystem services values across each zone type.

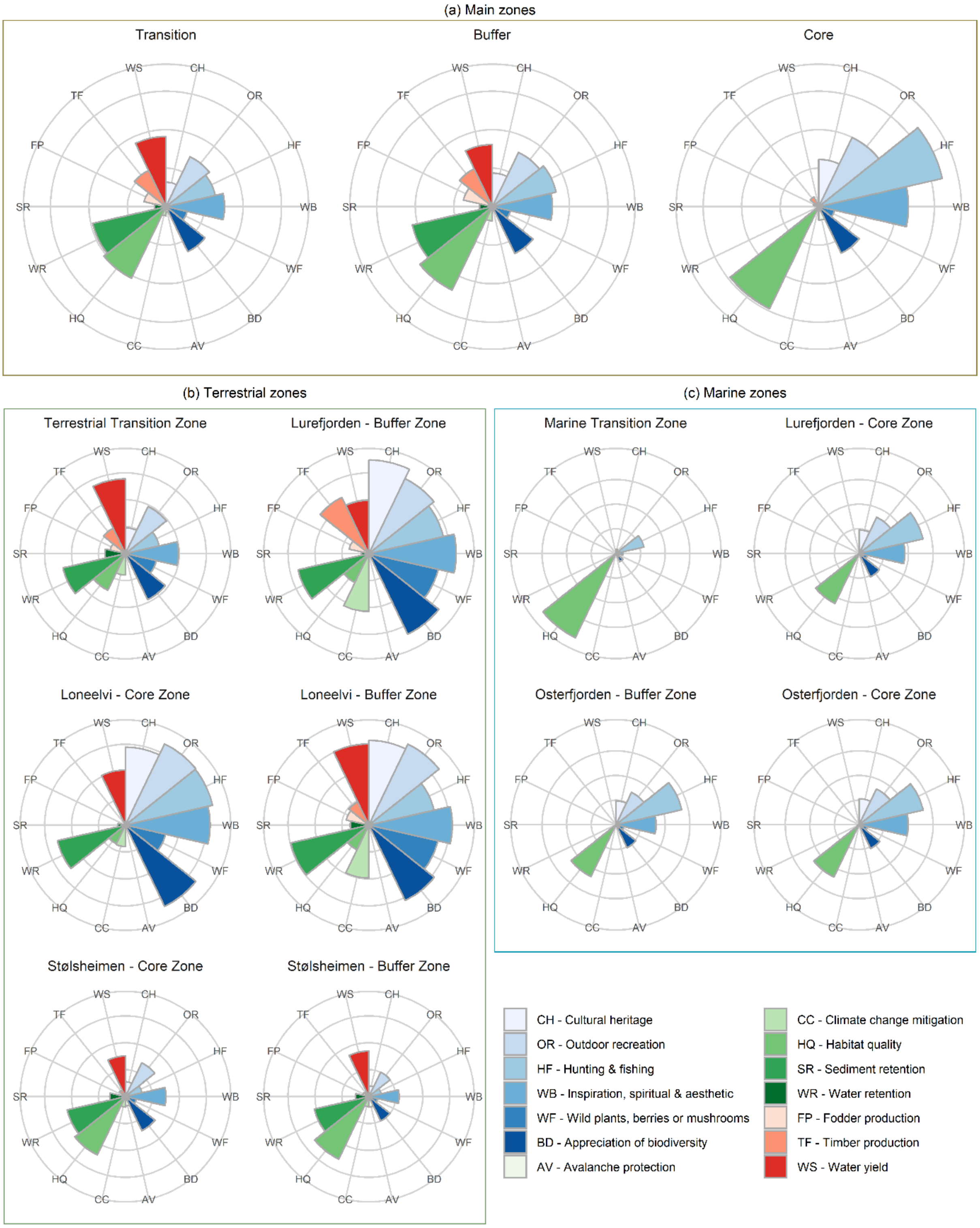

Figure 12. Median values of 14 ecosystem services in the (a) three main biosphere reserve zones, and individual zones separated into (b) terrestrial (and one freshwater) and (c) marine areas.

Ecosystem service bundles at two scales

Three bundles were identified at both the municipal and grid scale (Figure 13). The bundles at different scales were remarkably similar in their distribution and hence relative ecosystem service values. Bundle 1 had high values for cultural ecosystem services and was located in the lowland areas where most human settlements are. Bundle 2 was predominantly marine with high values for hunting and fishing and habitat quality. Bundle 4 was located in the more mountainous area to the east with high values for water supply and retention, and habitat quality. Broadly, Bundle 1 was very similar to the lowland terrestrial zone in relative ecosystem service values, Bundle 2 to the marine zones and Bundle 3 to the upland zones. Thus, the zonation of the biosphere reserve appears to capture each of the three distinct social-ecological system archetypes.

The similarity of the bundles at the two scales is due to the very strong and clear social-ecological gradients characterised by both the land- and water-forms, land-use intensity, and the human populations and associated infrastructure. The bundles therefore identify three distinct social-ecological system archetypes (Hamann et al., 2015). The similarity contrasts with the findings of Raudsepp-Hearne and Peterson (2016) who found a stronger influence of scale on the bundles. However, they also found that the number of ecosystem services assessed affects the bundles. In their study they only assessed seven ecosystem services at different scales whereas there are twice that many in our study. Further, the extent of our study site was significantly larger thus the potential to encompass large, distinct social-ecological systems is higher.

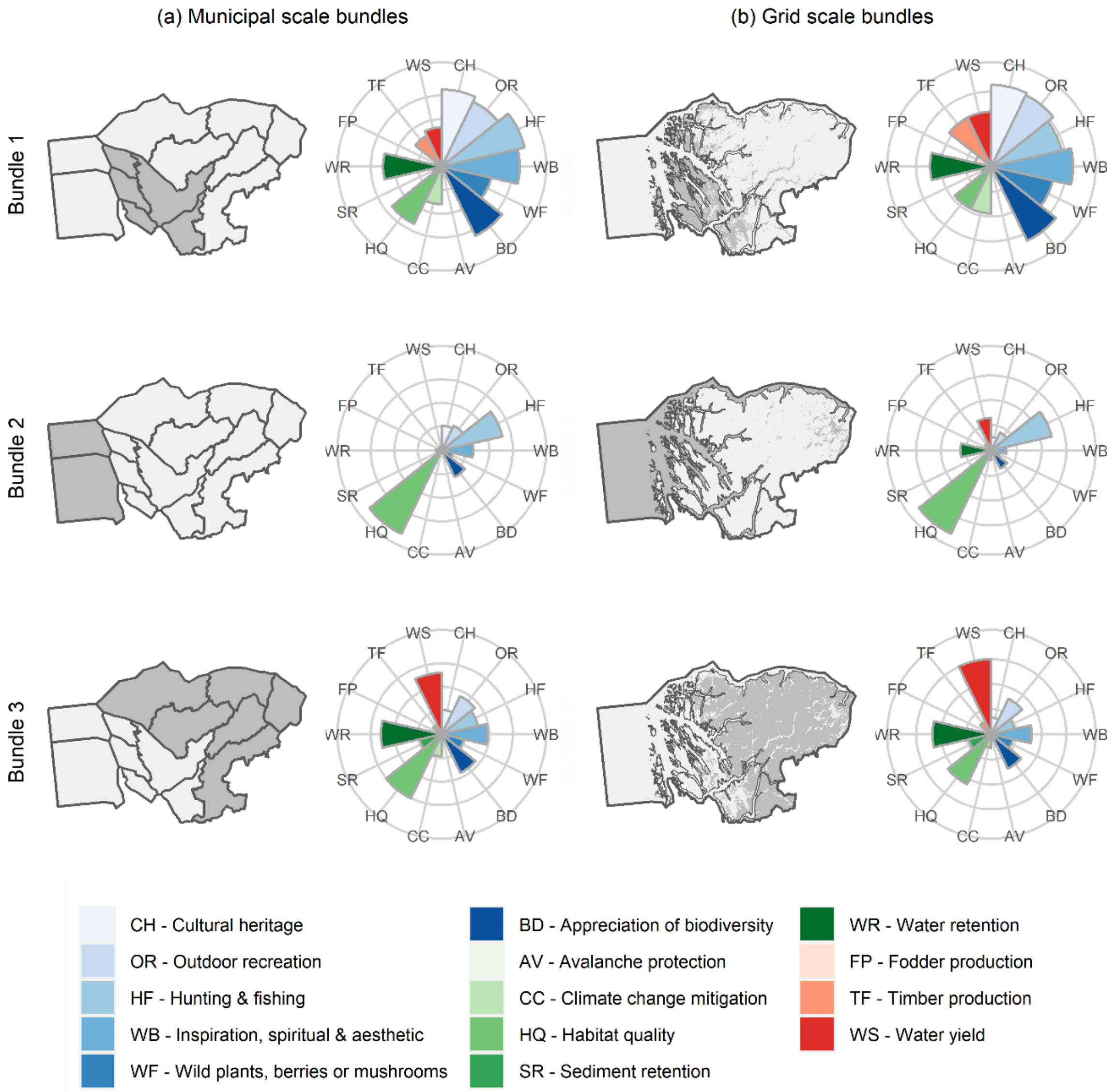

Figure 13. Distributions and mean values of 14 ecosystem services in the three bundles identified at (a) municipality and (b) grid (250 × 250 m) scales in Nordhordland Biosphere Reserve.

Social networks of ecosystem service co-production (Paper III)

Public values and governance, management, and research attention

The relative attention that different ecosystem services received through management, governance, or research and/or knowledge gathering were substantially different and were different from the relative public values assigned to the ecosystem services (Figure 14). Many ecosystem services were identified as directly managed, mainly livestock agriculture, clean air, water, and soil, outdoor activities, and local culture. Climate change mitigation, energy and protection from extreme weather received very little management attention. Ecosystem services that received the most governance attention were biodiversity, livestock agriculture, and hunting and fishing, while the least chosen ecosystem services were fruit and vegetable production, extreme weather event protection and wild food provision. Within research, biodiversity was the dominant ecosystem service identified followed by local culture, while the rest of the ecosystem services received relatively little research attention. The public valuation is the same as the mapped values in **Paper I** with outdoor activities dominating followed by biodiversity and metal wellbeing.

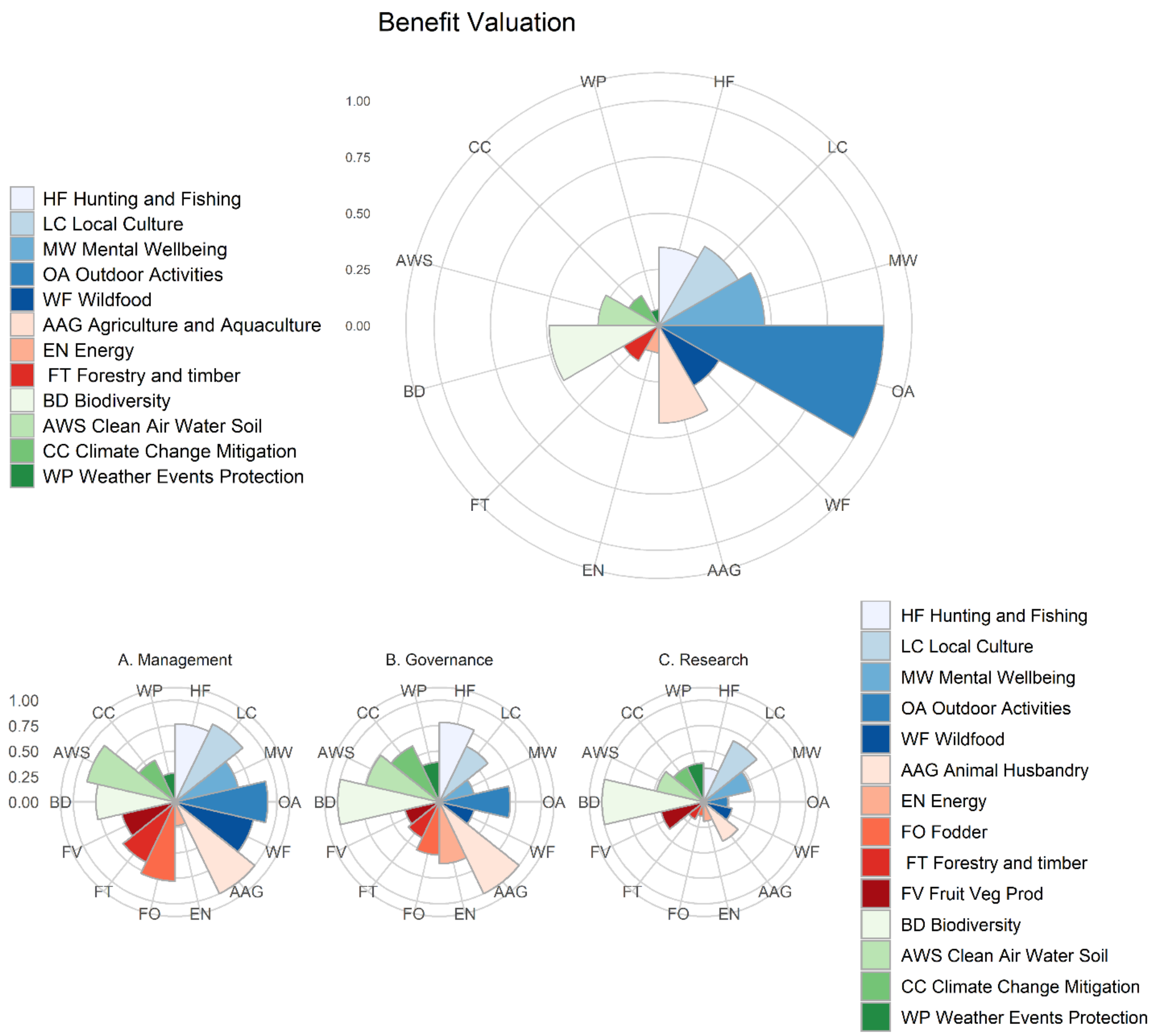

Figure 14. Relationships to the ecosystem services across Nordhordland Biosphere Reserve key stakeholders. Top panel: General public valuation of ecosystem services as obtained by a participatory geographic information system (PPGIS). Bottom panel: Ecosystem services connected to key stakeholders through management (A), governance (B) and research or knowledge gathering (C).

These results highlight several key potential mismatches in the management, governance and research attention that different ecosystems receive and the values that people assign to them. Notably, cultural ecosystem services are highly valued but receive comparatively less governance and particularly research attention.

Social networks

There were three distinct communities in the network communicating about ecosystem services (coloured polygons) and four clusters in relation to the specific ecosystem services that these stakeholders were connected (coloured nodes) (Figure 15). Farmers and local government had the most direct links (in- and out-degree centrality) to other nodes in the network which means that they communicate about ecosystem services with more different key stakeholder groups than others. The biosphere reserve organisation and regional government had the highest between centrality, suggesting that they act as bridges between key stakeholder groups working on ecosystem service management, governance and research/knowledge gathering.

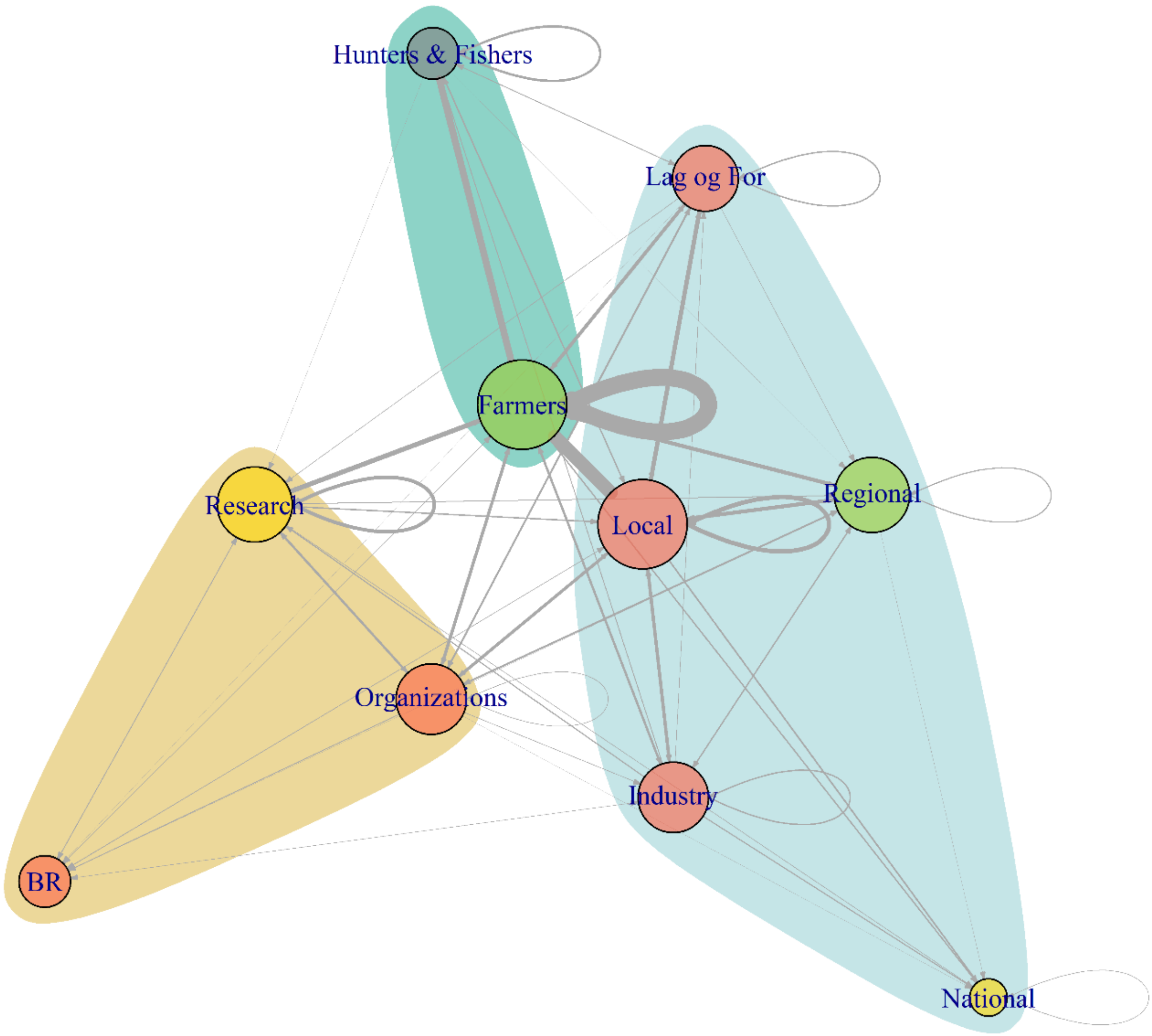

Figure 15. Simplified natural resource management social network of the Nordhordland UNESCO Biosphere Reserve area. Nodes are marked with the stakeholder classes outlined in Table 1 where BR stands for Biosphere Reserve organization. Large, coloured polygons show stakeholder membership to a network community while node colours refer the ecosystem service co-production clusters.

Social networks for the three ecosystem services classes were distinctive (Figure 16). The provisioning ecosystem service network was highly connected (high density) and most like the overall network (see Figure 15) with farmers and local government the most connected. In contrast to the overall network, however, the biosphere organisation was not identified as a *bridge* while local associations were, and four network communities were found. The other two ecosystem services networks were less connected than the provisioning network, the least connected being for cultural ecosystem services. The low connectivity highlights lack of cooperation in the management and governance of cultural ecosystem services which could be of concern given the high value placed on cultural ecosystem services by the public (see Figure 14). This is further complicated by the low level of connection to the network of some of the primary stewards (farmer, hunters, fishers) of highly valued cultural ecosystem services. Bridging organisations like the biosphere organisation and local governments can play a role here in improving dialogue and collaboration regarding the management and governance of these ecosystem services.

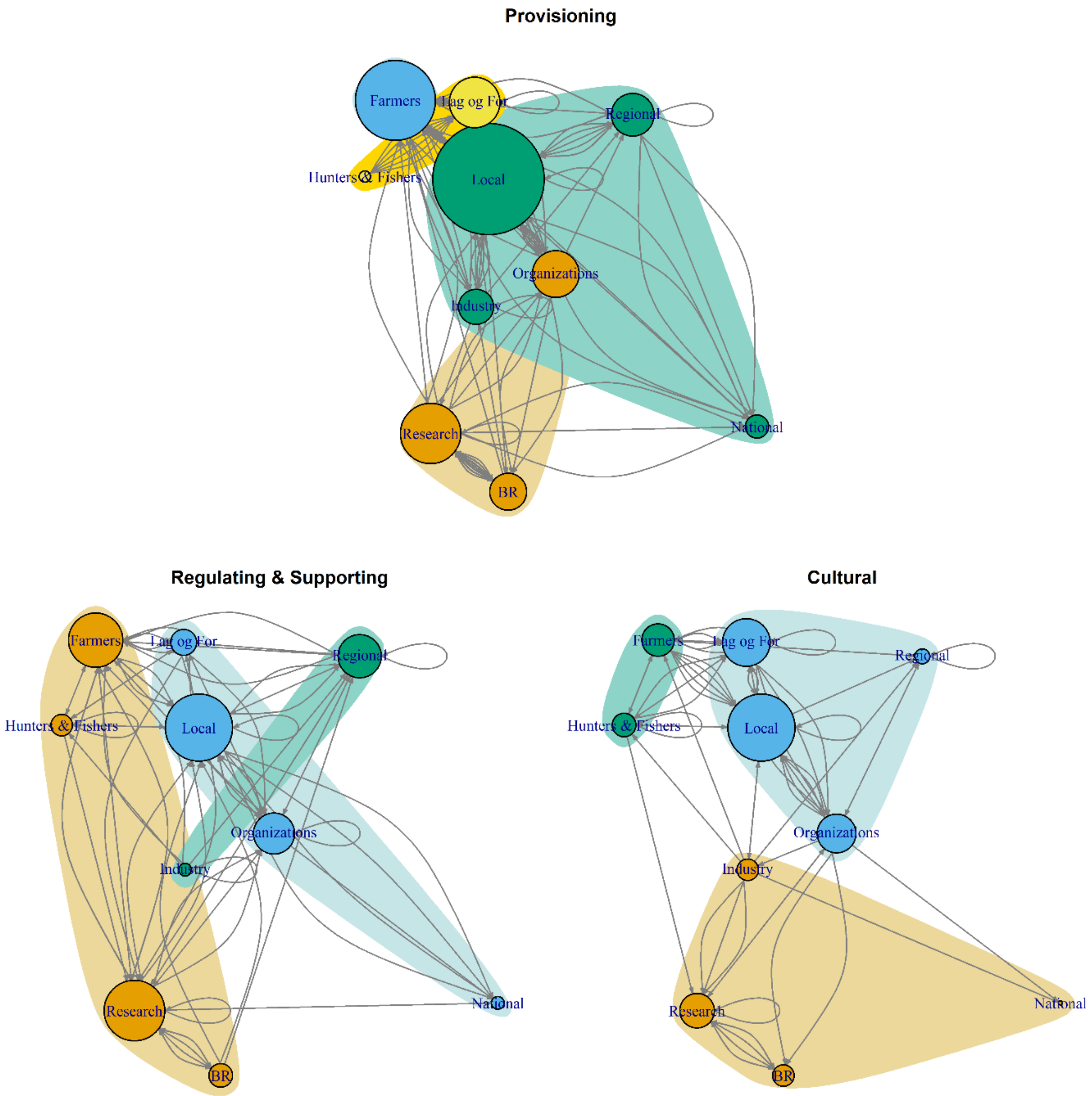

Figure 16. Social networks for all evaluated Ecosystem Services (ES) grouped into provisioning, regulating, and cultural ES. Size of node is a measure of centrality, both node and polygon colour show node community membership based on a network modularity cluster analysis.

Land-use change impacts on socio-cultural and biophysical ecosystem service values (Paper IV)

Biophysical values

Biophysical supply of ecosystem services was more similar than different in the different vegetation types, but some contrasts are clear (Figure 17). Open vegetation and natural forests tend to be more multifunctional but are unable to supply some key ecosystem services, most prominently timber. Importantly, planted forests are not superior at carbon storage compared to the other vegetation types calling into question their utility for climate mitigation. Instead, for biophysical multifunctionality natural forests allowed to grow along a successional trajectory may be a better choice than planted forests because there would be multiple ecosystem service benefits with this approach. Thus, it would be more beneficial to focus on restoration of native biodiversity and ecosystem services rather than tree planting for climate change mitigation alone (Tölgyesi, Buisson, Helm, Temperton, & Török, 2022). Critically, Norway spruce does not occur naturally in outer areas of western Norway (Birks et al., 2012) and therefore arguably does not meet the 'native' species criterion specified in Norway's climate forest programme (VKM et al., 2021).

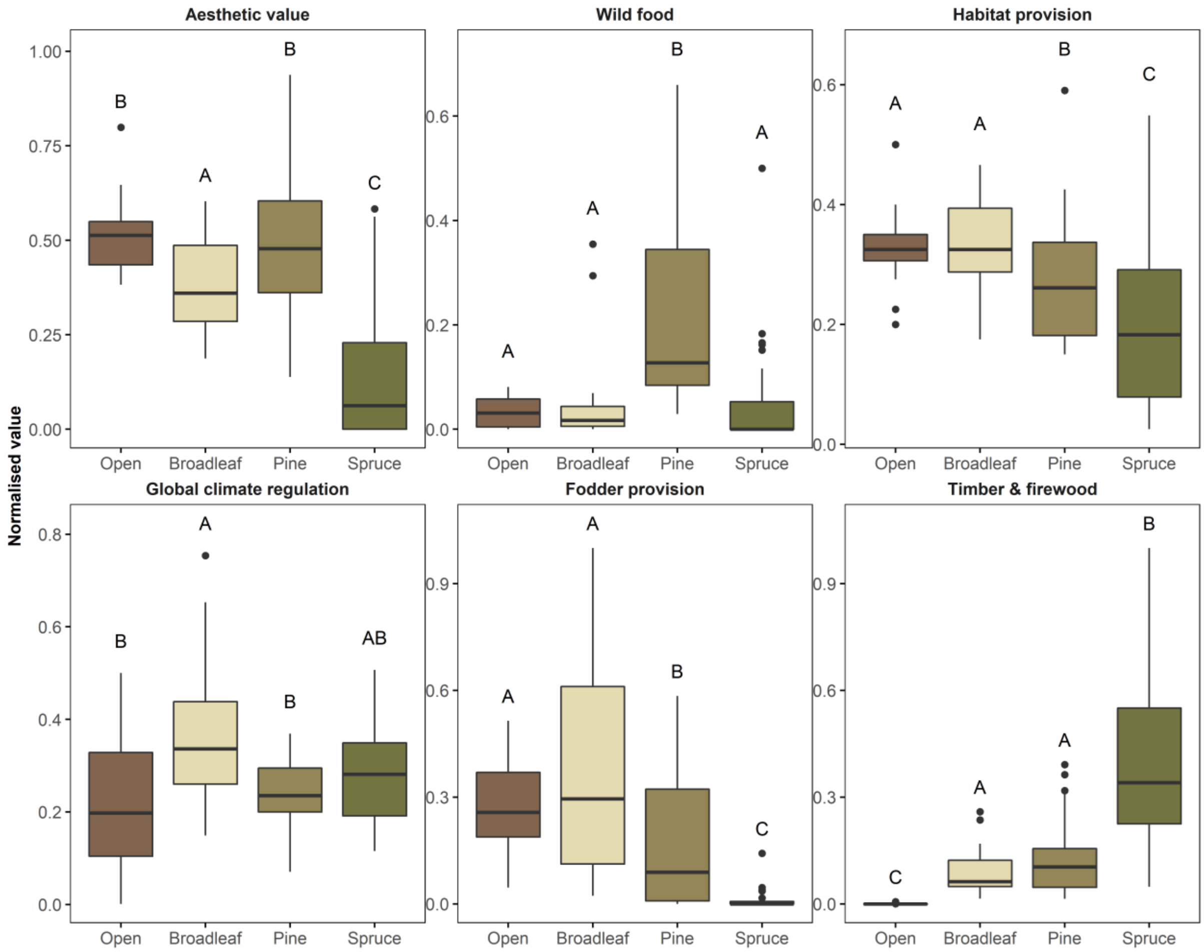

Figure 17. Boxplots of the normalised values for each ecosystem service in the different vegetation types. Box and whiskers that have different letters are significantly different ($p < 0.05$, pairwise Wilcox test; n = 33 sites; pine = 10, spruce = 11, broadleaf = 6, open = 6). Note that y-axes are on different scales to aid visualisation.

Socio-cultural values

In general, socio-cultural values for most ecosystem services were high in open vegetation and broadleaved forests, and pine forests to a lesser degree (Figure 18). Spruce forest, however, had low socio-cultural values and only wild food was valued higher than would be expect by chance. The low socio-cultural values for spruce forest is likely a place attachment response to preferences for historically common vegetation types like heathlands and livestock grazed open broadleaved forests that are typical of the mosaic cultural landscape in western Norway (Liu et al., 2021). Surprisingly, broadleaved forest was the only forest type significantly values for timber and firewood. It is likely that people have socio-cultural value for firewood harvesting because it is an activity that individuals undertake in broadleaved forest (primarily birch). In contrast, timber harvesting is generally a commercial activity in planted spruce forest.

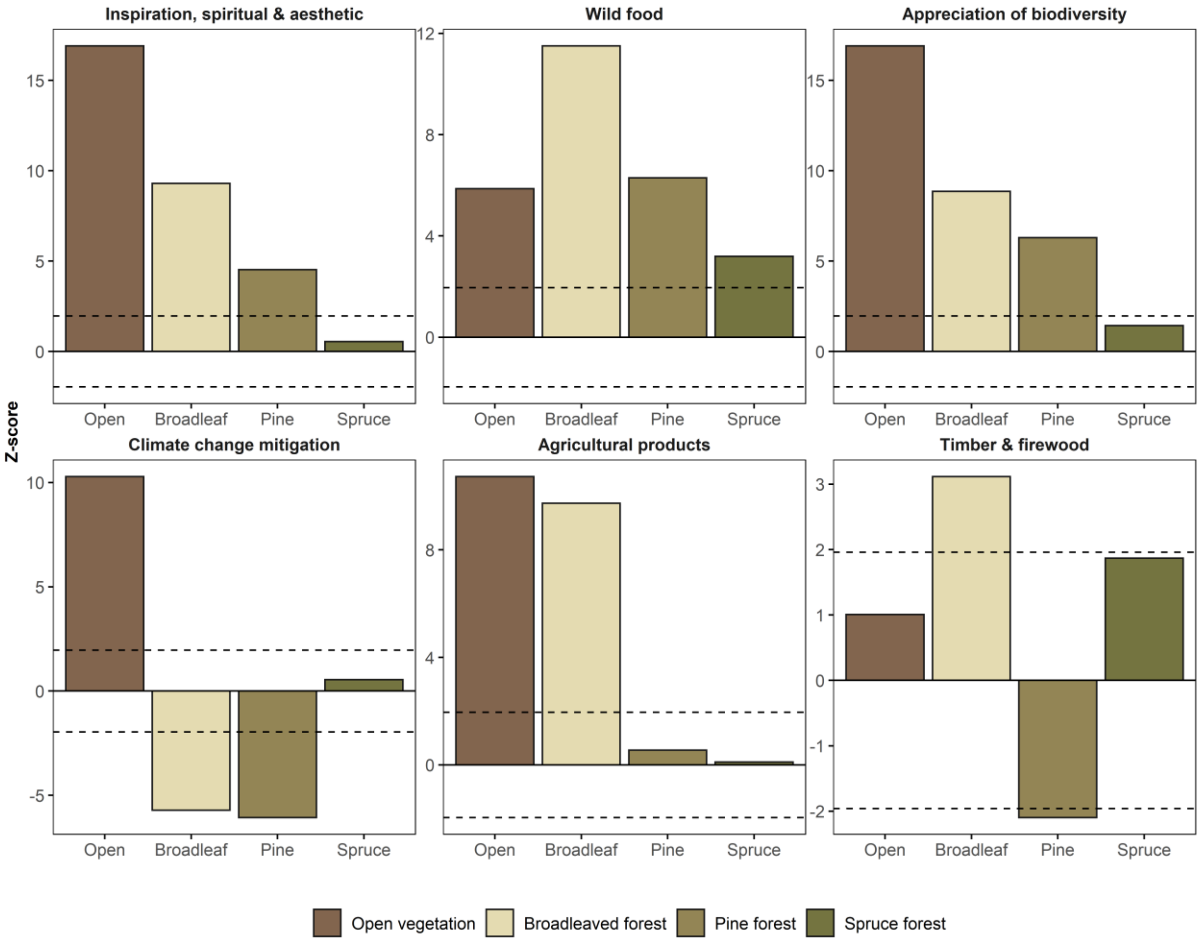

Figure 18. Z-scores of social-cultural values for ecosystem service in the four different vegetation types calculated from Public Participation GIS data. Values greater than 1.96 or less than -1.96 (horizontal dashed lines) show that the values are significantly higher or lower than would be expected by chance respectively. Note that y-axes are on different scales to aid visualisation.

Mapped socio-cultural values for ecosystem services were not evenly spread across the study participants. There were two distinct groups representing older farmers resident in the region with high values for provisioning ecosystem services on the one hand, and younger females that are not residents valuing regulating and maintenance, and cultural ecosystem services (Figure 19). These results are important for two reasons. Firstly, the common privileging of instrumental values (e.g., timber production) (Anderson et al., 2022) means that if those values were prioritised in planning decisions there would be negative effects on the values of young people and women who are disproportionately underrepresented in environmental decision making (Barraclough, Schultz, & Måren, 2021; Lundberg, 2018). Secondly, the values assigned by the primary stewards of the landscape (farmers) contrast with those of the wider public. This means that farmers hold the *responsibility* for maintaining values that they themselves do not strongly hold raising the question about who should steward those values. I argue that broad societal participation can be an important way to steward these landscapes which requires establishment and fostering of partnerships between farmers, local communities and authorities and nature conservation societies (Bridgewater, 2017).

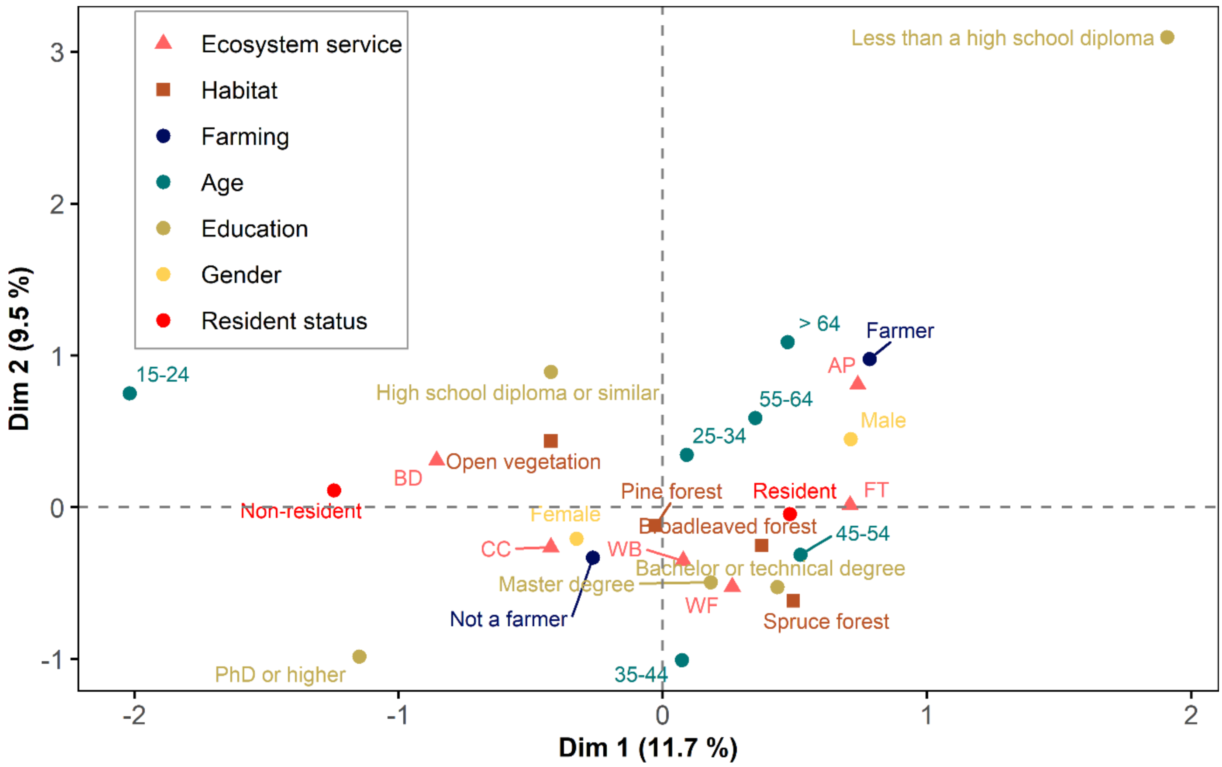

Figure 19. Biplot of the first two dimensions of the multiple correspondence analysis of the mapped ecosystem services, habitat types, and five socio-demographic variables. CC = Climate change mitigation, BD = Appreciation of biodiversity, AP = Agricultural products, FT = Firewood & timber, WB = Inspiration, spiritual & aesthetic, WF = Wild foods.

(Mis)match of biophysical and socio-cultural values

Matches between biophysical and socio-cultural values were common with very strong overall matches for biodiversity and agricultural products, strong matches for aesthetic value and wild food, moderate for timber and firewood and weak for global climate regulation (Table 3). The strong match in biodiversity suggests that peoples' perceptions of biodiversity and actual biodiversity are relatively consistent (e.g., Lindemann-

Matthies, Junge, & Matthies, 2010). The match of agricultural products suggests local knowledge corresponds with the historical role of open vegetation and broadleaved forests as outfield grazing resources. The weak match in global climate regulation is a little more complex. However, the multiple correspondence analysis reveals a potential explanation. Values for climate regulation in open vegetation was associated with younger females with higher levels of education. It is possible that this group is socially aware of the value of heathlands for carbon storage which is a topical issue in western Norway. However, it is also important to acknowledge that the biophysical values were very similar and the only strong evidence of a difference (cf. Muff, Nilsen, O'Hara, & Nater, 2022) was between pine forest and broadleaved forest (p = 0.006).

Table 3. Cross comparison between socio-cultural and biophysical values for ecosystem services in the four vegetation types. The direction of the arrows and colours show whether the rank of socio-cultural value was higher (↑), lower (↓) or not different (↔) to biophysical values in each vegetation type. See the legend for more details of colours and symbols.

Ecosystem service	Vegetation type				Overall (mis)match
	Open	Broadleaf	Pine	Spruce	
Aesthetic value	↔	↑	↓	↔	Strong
Wild food	↔	↑	↓	↔	Strong
Biodiversity	↔	↔	↔	↔	Very strong
Climate regulation	↑	↓	↓	↔	Weak
Agricultural products	↔	↔	↔	↔	Very strong
Timber & firewood	↔	↑	↔	↓	Moderate

Legend

Colour/ symbol	Description
↔	The same rank
↓↑	One rank higher or lower
↓↑	Two ranks higher or lower
↓↑	Three ranks higher or lower

Colour	Description
Very strong	All ranks match
Strong	Three ranks match
Moderate	Two ranks match
Weak	One rank matches
Very weak	No ranks match

DISCUSSION

The aim of this thesis was to map ecosystems services in Nordhordland Biosphere Reserve, integrate local knowledge and perceptions of ecosystems and their services related land-use change, and implement citizen science projects for knowledge co-production. Below I explore how the papers presented in this thesis addressed three sub-aims that I distinguish under the following headings: (i) *Mapping ecosystem services*, (ii) *Ecosystem services and land-use change*, and (iii) *The methodological thread (or the citizen science part)*. Under each sub-aim I point to the key findings, identify the important contributions that I make either in methodology or theory, and then explore potential future directions of research that can extend or draw on my work. In addition, given the case study and biosphere reserve focus, I reflect on the future directions of this work for the Nordhordland Biosphere Reserve as well as for biosphere reserves more generally.

Mapping ecosystem services

The first sub-aim of this thesis was to map ecosystem services in Nordhordland Biosphere Reserve. In general, ecosystem service mapping tends to be focussed on single value-domains, most prominently biophysical and socio-cultural (Scholte et al., 2015). In this thesis I mapped ecosystems services in the socio-cultural value-domain (**Paper I** and **II**) which I then integrated with the biophysical value-domain (**Paper II**). The cross value-domain method presented in **Paper II** is an important advancement to align ecosystem service mapping with the modern literature on the multiple ways that nature contributes to wellbeing (Pascual et al., 2017). In addition to mapping the ecosystem services, I used bundles of ecosystem services to first explore the cooccurrence of socio-cultural values within one value-domain (**Paper I**) and then to map social-ecological system archetypes using both value-domains (**Paper II**).

The socio-cultural bundles in **Paper I** were particularly informative in identifying places with linked values for (i) agriculture and cultural heritage, (ii) outdoor recreation and biodiversity, and (iii) wild food and mental wellbeing (inspiration, spiritual and aesthetic combined). I interpret these bundles as identifying biocultural values, which I describe as the importance, worth or usefulness that people assign to the linked biological and cultural aspects of ecosystems. These insights compliment the growing literature that recognises the importance of biocultural approaches for addressing sustainability and biodiversity conservation challenges (Bridgewater & Rotherham, 2019; Hanspach et al., 2020). It is important to acknowledge that this work provides quantitative data on spatial distributions of values, but it does not uncover underlying motivations for the linked values. I did uncover some socio-demographic explanations for ecosystems service values in **Paper IV,** however, a richer explanation is still lacking. Disentangling these explanations would require additional open questions in a survey, or alternative methodologies such as semi-structured interviews with selected participants. It was a conscious choice to not include additional questions in the survey at the time because it was already substantial. However, these questions are now being explored in a follow-up project in the region using open questions and semi-structured interviews, facilitated by photo elicitation, which should yield some exciting results.

Integrating socio-cultural and biophysical (ecological) domains for mapping and bundling ecosystem services is rare and **Paper II** provides an important advancement in the pursuit of integration. The bundles in **Paper II** are therefore interpreted as social-ecological system archetypes because of these integrated methods (Hamann et al., 2015). This interpretation was strengthened by the intuitiveness of the bundle distribution which followed clear social-ecological gradients. The strength of the gradients revealed a close concurrence between the two scales in both the distribution and the relative ecosystem services values. This is an important contribution to the ongoing question regarding the generality of scaling effects on ecosystem service bundles, and what the different factors that influence scaling effects are (Meacham et al., 2022; Raudsepp-Hearne & Peterson, 2016; Saidi & Spray, 2018). Despite the strong concurrence between scales, it is important to point out that the spatial overlap was nonetheless imperfect which was not analysed in detail. Identifying where and why the mismatches occur at different scales would be key for operationalising the findings for management and planning (Crouzat et al., 2015), hence an important area for future research. Additional research that would strengthen the work on social-ecological system archetypes would be to consider a wider range of social-ecological variables

(Rocha, Malmborg, Gordon, Brauman, & DeClerck, 2020), and explore new ways to explain the bundle distributions that use data independent of the data used for ecosystem service modelling and mapping.

The use of predictive modelling with PPGIS for the cultural ecosystems services contributes to improving mapping cultural ecosystem service supply for integrated bundle mapping (**Paper II**). First, PPGIS is particularly strong at eliciting responses for a diverse number of cultural ecosystem services (**Paper I**) which has been challenging to date (Brown & Fagerholm, 2015; Fagerholm et al., 2019). Second, the predictive modelling addresses issues with under-mapping that density-based measures such as point- and kernel-density do not account for. Point density is unable to assign value to places that have not been mapped and represents actual use by study participants only, while kernel density lacks the specificity of predictive modelling. Third, predictive modelling advances theory because the model allows the identification of the relative strengths of different variables in determining the distribution of individual ecosystem service values (**Paper II**), or value bundles (**Paper I)**. Finally, predictive modelling and biophysical modelling can be done at the same scale, often using the same underlying data (e.g., land cover, elevation), which enables testing of scaling effects on ecosystem service bundles (**Paper II**).

In **Paper III** we mapped not the spatial distribution of ecosystem services, but the co-production network of those ecosystem services. The novel application of PPGIS with a social-network analysis in **Paper III** addresses a key component of the ecosystem services governance literature. Although the application of social network approaches to natural resource management is not novel (Bodin & Chen, 2023; Mason, Olander, Grala, Galik, & Gordon, 2020), using social networks approaches to disentangle the governance of distinct types of services is a novel contribution of this work. The paper makes three main contributions by (i) conceptualising ecosystem service co-production as a *relational network*, (ii) considering not only whom discusses with whom but also the ecosystem services that they discuss, and (iii) including co-production relationships that are not only direct modification (e.g., research attention).

Ecosystem services and land-use change

The work presented in **Paper VI** addresses two key land use change issues – rural abandonment and afforestation, with a focus on sub-aim "knowledge and perceptions of ecosystem services". In this paper we show that traditional land uses managed by farmers are highly valued by a broad sector of society. This result uncovers an imbalance in who benefits from and who manages the landscape. We uncovered a similar result in **Paper III** with high values for cultural ecosystem services being expressed by society at large, but with farmers being the primary managers of those ecosystem services. **Paper III** further identified that as the key managers of cultural ecosystem services, farmers are largely missing from the broader governance network of those ecosystem services. It is therefore unreasonable to place the responsibility of stewardship solely on the plate of farmers. Broader participation in landscape stewardship requires establishment and fostering of partnerships between farmers, local communities and authorities and nature conservation societies (Bridgewater, 2017) which we show is currently lacking (**Paper III**). Involvement of farmers is critical not only because they are usually the landowners, but because of the important traditional ecological knowledge they hold. For example, the traditional practice of burning for managing the successional pathway of heathlands requires this form of knowledge (Kaland & Kvamme, 2014; Måren, 2009). These activities are often better served with sufficient person-power: tree removal is hard work, and our results can provide important guidance to inform campaigns for engaging groups that hold particular values to participate in landscape management. For example, we find that in general, younger people that do not reside in the region hold values for biodiversity and global climate regulation in open heathland vegetation. We can infer that this group is representative of university students, likely studying in environmental programmes. This information can point to productive places and themes for engagement with landscape stewardship. A potentially fruitful line of research would be to study known cross-sectoral partnerships involved in cultural landscape stewardship to understand motivations to work together and values among different actors. There are several activities organised in the forms of *dugnad,* voluntary communal effort, related to cultural landscape management in the region such as removing trees from overgrowing heathland or heathland burning organised by the

Nature Protection Society (*Naturvernforbundet*). These would be key projects to target for such research.

Globally there are numerous tree planting initiatives including the *The Nature Conservancy's Plant a Billion Trees* campaign, the *Trillion Tree Campaign* and my home country of New Zealand's own *One Billion Trees* programme. All these programmes purport to be our saviour from climate change. But many of them fail to consider the wider implications of tree planting on both ecological and social systems. However, there is an increasing body of evidence building, and a public discourse that questions the utility of planted forests for carbon sequestration as well as a wider range of values (e.g., Liu et al., 2021; Strand, Fjellstad, Jackson-Blake, & De Wit, 2021; Suryaningrum, Jarvis, Buckley, Hall, & Case, 2022). **Paper IV** contributes to a critical awareness of the Norwegian policy surrounding so-called *climate forests* with a novel multi-method approach that covers biophysical and socio-cultural values-domains. It should be noted that the results uncovered in **Paper IV** have some place specific implications which may not be universally applicable. For example, countries that have undergone dramatic and more recent land clearances for agriculture may have distinctly different perceptions of forest ecosystem services than in western Norway.

The methodological thread (or the citizen science part)

The different papers presented in this thesis *showcase* different ways in which PPGIS can be used for ecosystem service mapping and assessments. In this thesis PPGIS data is used on its own (**Paper I**), and in combination with other data types including modelled biophysical data (**Paper II**), social network data (**Paper III**) and field based ecological data (**Paper IV**). The first two papers show application of PPGIS data collected for the specific task of producing spatial data for further analysis, while the second two show novel applications. First, the approach in **Paper I** built on a growing literature that uses PPGIS for mapping ecosystem services values and perceptions (e.g., Brown & Fagerholm, 2015; Fagerholm et al., 2016; Garcia-Martin et al., 2017). Although some of the findings were confirmatory, like the predominance of outdoor recreation and importance of accessibility for value mapping, the bundles revealed some interesting insights. In particular, the spatial cooccurrence of cultural heritage and agricultural values is a distinctive feature of landscapes with long agrarian histories (see *Mapping ecosystem services* above). Second, with so few studies that integrate PPGIS with biophysical mapping **Paper II** compliments recent literature on the topic (Bagstad, Reed, Semmens, Sherrouse, & Troy, 2016; Rolo et al., 2021). Third, **Paper III** capitalises on web-based platform for PPGIS surveys by linking public mapping with ecosystem service co-production social-networks. Co-production networks that considers both *which ecosystem services* are be discussed and with *whom* is underexplored and presents a strong methodological advancement in sustainability science (Bodin & Chen, 2023). Finally, the novel mix of PPGIS and ecological field surveys in **Paper IV** demonstrates how PPGIS data collected for one purpose can be co-opted for other uses such as the integrated multi-method study presented. See *Covid-19 and 'the last chapter'* below for more on this need to co-opt the data.

Reflecting on the sub-aim of *citizen science projects to facilitate co-production of knowledge* I argue that the PPGIS component has been implemented as a citizen science project. Citizen science is broadly defined engaging the public or non-scientists in scientific research tasks (Vohland et al., 2021). However, the usage of *citizen science* is variable across the literature and Haklay et al. (2021) identified over 30 formal definitions of the term. The definitions span from citizens simply being involved in data collection, for example such as opportunistic biodiversity data uploaded to platforms such as *iNaturalist*, to definitions that mention co-design, co-collection, and co-production. Citizen science has also been explicitly used to describe crowdsourced PPGIS data, although the level of engagement of the public in the process can vary from simple point mapping to assisting in study design and data analysis (Jarvis, Bollard Breen, Krägeloh, & Billington, 2015; Thompson & Arceneaux, 2022). In PPGIS value mapping survey participants are not particularly engaged in scientific work and could be classified as the study subjects. But participatory methods have been shown to encourage learning and foster ongoing engagement in environmental issues. In this thesis, I believe it is reasonable to draw the link between the PPGIS and citizen science based on the role that citizens have played in data collection. However, citizen involvement in a more interactive co-production approach may better serve enriched learning for the citizens themselves.

Contribution to, and future directions for biosphere reserves

To the World Network of Biosphere Reserves

Through biosphere reserves, UNESCO's Man and the Biosphere Programme has the strategic objective to "conserve biodiversity, restore and enhance ecosystem services, and foster the sustainable use of natural resources" (UNESCO, 2017, p. 17). The primary functions of biosphere reserves: (1) conservation, (2) sustainable development and (3) logistic support for project, education, research, and monitoring are operationalised with the zonation system. There is an implicit assumption that the zonation should achieve those goals. The approach taken in **Paper I** and **Paper II** with explicit focus on the zonation contributes to understanding whether biosphere reserve zonation promotes the functions of biosphere reserves. Despite the importance of the zonation system and ecosystem services in achieving the objectives of biosphere reserves there is limited knowledge on ecosystem services values across biosphere reserve zones (Castillo-Eguskitza et al., 2019; Palliwoda et al., 2021). The work presented in this thesis contributes by explicitly pointing to the need to consider the *social-ecological context* of biosphere zones in ecosystem service valuation, *not* only their *identity* as core, buffer or transition zones.

Some biosphere reserves use the UN Sustainable Development Goals (SDGs) (United Nations, 2015) as a foundation for reporting on their progress towards meeting the goal of balancing sustainable development and biodiversity conservation. For example, Clayoquot Sound Biosphere Region reports on the state of the region using a tool called *Vital Signs* which is explicitly based on SDG indicators (Clayoquot Biosphere Trust, 2018). Ecosystem services can be applied to reporting tools such as is used in *Vital Signs* because of the links between ecosystem services and the SDGs and their indicators (Wood et al., 2018). The potential for ecosystem services to contribute to SDG reporting has been identified by Vasseur and Siron (2019) who call for a consistent protocol for ecosystem service assessments in biosphere reserves. In their call there are four steps to define and assess the ecosystem services in biosphere reserves: (i) define the objectives and priorities for the biosphere reserve, (ii) select the key ecosystem services within the biosphere reserve, (iii) work together to assess the ecosystem services and (iv) monitor the ecosystem services over time. In their report the steps are presented as a linear process, however, it is probably more appropriate to consider it as cyclical whereby findings from ecosystem service assessments can feedback into revaluating objectives and priorities (Figure 20). Such an approach would be well suited to biosphere reserves because adaptive co-management is promoted within the biosphere reserve model and adaptation from learning and new knowledge is actively encouraged.

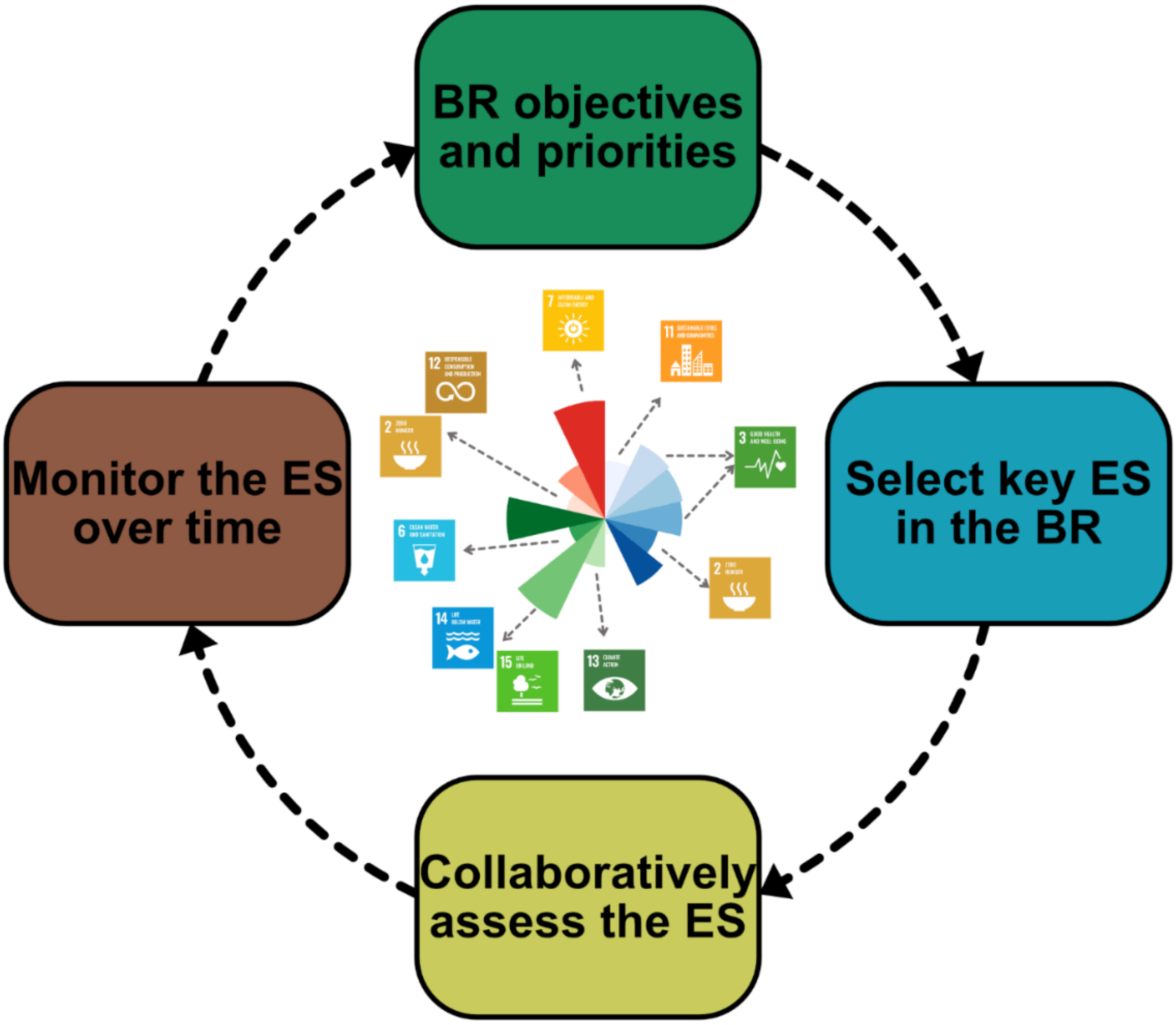

Figure 20. A proposed approach to ecosystem service assessment in biosphere reserves linking ecosystem services to the UN Sustainable Development Goals. Adapted from Vasseur and Siron (2019). ES=Ecosystem Services, BR=Biosphere Reserve.

To Nordhordland Biosphere Reserve

An important part of the work that contributed to **Paper I** and **II** was stakeholder engagement. The ecosystem services were selected in a multi-step process that included: (i) expert selection, (ii) academic literature review and (ii) stakeholder refinement. These steps were important to locally contextualise the ecosystem service typologies. Such an approach has been shown to result in improved learning and understanding from key stakeholder involved in decision making (Malmborg et al., 2021). Although not specifically addressed in this thesis, I have anecdotally seen some evidence of this learning in follow-up engagement processes with key stakeholders. In the context of my PhD research there has been a significant and growing interest in the PPGIS and survey. Colleagues (Alícia Barraclough and Inger Måren) and I have presented results from the survey (**Paper I)** and the social network **(Paper III**) to key stakeholders (Figure 21), many of whom have been involved since the conception of my PhD project, but also during the development of Nordhordland Biosphere Reserve as a candidate area. During these workshops participants showed a keen interest in the results. For example, several participants pointed out the importance of farmers knowing that the landscapes they manage are valued by so many (**Paper I**) but also that the ecosystem services they manage received little attention from governance and research (**Paper III**). This interest has also now spilled over into several projects that 'follow on' from the work we have done. The biosphere reserve organisation has requested that the PPGIS survey be relaunched as a tool for engagement of the public in the biosphere reserve as well as ecosystem services (*naturgoder*). This could prove a fruitful endeavour because there is still some way to go with public learning related to the ecosystem services concept. In a recent national survey in Norway less than 30% of respondents had heard of the term and only 10% percent knew what it meant (Miljødirektoratet, 2021). Municipality planners have registered interest in data from the PPGIS survey being made available for them as decision support in planning projects where conflicts of values and development are inevitable.

Figure 21. Dissemination of the results from the participatory mapping survey to key stakeholders along with a follow-up workshop in Nordhordland Biosphere Reserve with local politicians.

AN EPILOGUE OR SOME REFLECTIONS ON THE PHD EXPERIENCE

The chance to be part of this happens briefly. The invitation is not to show how inventive and imaginative you are, but how much you can ***notice what you are already a part of****. And appreciate it and share it. And care about those that are around. Look out for their welfare while you look out for your own. That's it!*

– Burgs in Mt. Wolf, Red

A disciplinary journey

At the start of my PhD I might have identified as an ecologist, but over the last three and a bit years I have moved towards a more interdisciplinary sustainability scientist (Haider et al., 2018). What this means is that rather than being bound to a single discipline and working in a multidisciplinary team where each individual contributes from their own discipline, I view myself as 'undisciplined', an interdisciplinary individual (Haider et al., 2018; Robinson, 2008). This has been an important part of working within the ecosystem services framework which is so disciplinary diverse. To date much of my education has been embedded within environmental and natural sciences. My working life following that education was centred more on policy implementation and monitoring in local government, followed by period in consulting assessing ecological impacts and providing advice to minimise those impacts. In this work I observed and realised that decisions about environmental and ecological issues are typically informed by one set of experts (me) and then interpreted and made by another set of experts (planners). Unfortunately, many of these decisions lacked rigorous and broad consultation, and when consultation was undertaken, it was usually on a case-by-case basis. These narrowly focussed approaches naturally excludes large parts of society and their the socio-cultural values for nature leading to reduced wellbeing of both the human and more than human (Chan et al., 2016). This led me to question my role as the 'expert' and reconsider the way in which natural resource management decisions are made. Importantly, how can we account for the multiple values of nature (Kenter, 2018; Pascual et al., 2021; Pascual et al., 2017).

It is commonly said that ongoing academic education and training, such as taking a PhD, involves increasingly more focus on a very specific topic. It seems that for me this is both absolutely true and absolutely false at the same time. On the one hand, ecosystem services and a social-ecological systems approach has broadened my horizons and taken me down diverse paths of learning and interest that I would not have expected. In fact, it has been a challenge to keep focused and not stray too far from the topic at hand and *getting lost* in the literature. From my quantitative ecology and applied backgrounds, and my tendency to enjoy mixing it up, I think I have stumbled into a field of research that suits me. I have been able to apply ecological methods like maximum entropy modelling and quantitative field work *and* think about the *real-world* use of the knowledge as something tangible. I have also been able to explore an exciting new area of human-nature relations that has for a long time interested me outside of academic work. It has been exciting to have the opportunity to bridge my personal interests and academic work.

On the other hand, it seems that I have become a 'PPGIS of socio-cultural values for ecosystem services in biosphere reserves person'. Building on the work in my thesis there are now several projects that I am already involved in. Two that I am actively working on map ecosystem services with PPGIS in (i) all 12 of Portugal's biosphere reserves and follow-up in Nordhordland Biosphere Reserve. In addition, I have been engaged by a biosphere reserve in Sweden to help set up a PPGIS for them. The success of this work has been incredibly rewarding to see and I look forward to engaging with a wider peer group in the near future on this topic.

Covid-19 and 'the last chapter'

In my original plans **Paper IV** looked very different. I had planned on-farm field surveys to assess 'climate regulation in agricultural land-uses' for summer 2020 along with farmer interviews. Summer 2020 turned out to be the summer of COVID-19 which meant that movement was restricted and face-to-face interviews to coincide with field surveys was not going to happen. In the end field surveys were planned on land that was not actively used to coincide with late summer when berries were ripening, and mushrooms were emerging, to help us assess wild-food supply. This is where I co-opted the PPGIS. In the end I am satisfied with the work – and we got to eat lots of mushrooms in 2020 and 2021 (Figure 22).

Figure 22. A beautiful mix of chanterelle/kantarell (*Cantharellus cibarius*), yellow legs/traktkantarelll (*Craterellus tubaeformis*) and saffron milk cap/furumatriske (*Lactarius deliciousus*) collected in 2021.

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PAPER I

Participatory mapping reveals biocultural and nature values in the shared landscape of a Nordic UNESCO Biosphere Reserve

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Sheep mustering (*sauesanking*) in Stølsheimen, Masfjordern Municipality. Sheep mustering requires coordination among members of a grazing group (*beitelag*) and takes place over a weekend in late summer-early autumn. Photo: Jarrod Cusens.

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RESEARCH ARTICLE

Participatory mapping reveals biocultural and nature values in the shared landscape of a Nordic UNESCO Biosphere Reserve

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Abstract

1. Making the right decisions for sustainable development requires sound knowledge of the values and spatial distribution of the services co-produced by ecosystems and people. UNESCO's Man and the Biosphere programme and associated Biosphere Reserves (BRs) are key learning sites or model regions for sustainable development providing key entry points for transdisciplinary work on sustainable development. However, there is limited research exploring spatial distribution of socio-cultural Ecosystem Service (ES) values in BRs and how those values vary according to the BR zonation.
2. We used a transdisciplinary approach to design and implement a public participation geographical information systems (PPGIS) survey in a recently designated BR to (a) asses the spatial distribution of ES values in the different zones, (b) identify hotspots of ES values, (c) identify spatial bundles of ES values and (d) assess the social-ecological characteristics that determine the distribution of those values.
3. We found that stakeholders identify high biocultural ES values, mapping predominantly places for outdoor recreation, biodiversity, agricultural products and cultural heritage. Buffer zones had high agricultural and cultural heritage values while extractive values were largely absent from cores zones. We identified five spatial ES-value bundles highlighting distinct places important for ES values related to ‘multifunctional landscapes’ located close to settlements, ‘cultural landscapes’ associated with agricultural land, ‘wild animal resources’ along the coastlines, ‘outdoor recreation and biodiversity’ and ‘passive cultural values’ widely distributed in high and moderately populated areas.
4. We found that accessibility was important for ES values and that people value nature close to where they live. We show the importance of biocultural values in the region, and agricultural landscapes were highly valued for multiple ES values beyond agricultural products alone.
5. We show that BRs have become places that link cultural heritage, agricultural and biodiversity values in multifunctional landscapes. We put our findings into the local context and suggest how they can inform land-use planning and management through policies aimed at maintaining key agricultural landscapes that

provide social-ecological resilience. Additionally, we discuss the value of our study for the wider BR network and how similar work can contribute to monitoring of BR implementation.

KEYWORDS

Biosphere Reserve, ecosystem services, Man and the Biosphere programme, nature's contributions to people, public participation geographical information systems, sustainable development, transdisciplinarity

1 | INTRODUCTION

Today, we are facing global sustainability challenges that are complex and interconnected. Human activities such as land-use change are contributing to the biodiversity crisis and simultaneously impacting our own well-being. To address these challenges, we need to develop a holistic understanding of multifunctional landscapes that work for biodiversity and people (Kremen & Merenlender, 2018). In 1971, UNESCO launched the Man and the Biosphere (MAB) programme which aims 'to establish a scientific basis for improvement of relationships between people and their environments' (UNESCO, 2017, p. 12). In 1974, MAB began designating Biosphere Reserves (BRs) which today comprises 727 BRs in 131 countries in the World Network of Biosphere Reserves. These BRs are examples of social-ecological systems spanning numerous biomes and ecosystems that have been described broadly as learning sites, living laboratories or model regions for sustainable development (Kratzer, 2018; Schultz et al., 2018; Starger, 2016) forming the basis for implementation of the recently updated *MAB Strategy* (2015–2025) and the *Lima Action Plan* (2016–2025) (UNESCO, 2017). The *Lima Action Plan* clearly highlights BRs as sites that are expected to be sources and stewards of ecosystem services (ES) and that contribute to achieving the UN Sustainable Development Goals (SDGs) (United Nations, 2015).

The Seville Strategy (UNESCO, 1996) gives BRs three primary interconnected functions: (a) conservation, (b) sustainable development and (c) logistic support for project, education, research and monitoring, and these are implemented through a system of zonation comprising core, buffer and transition zones. Importantly, 'conservation' across the BR refers not only to biodiversity conservation, but also to cultural diversity conservation. The focus on biocultural diversity and the consideration of 'people and nature' (Mace, 2014; Pascual et al., 2021) align BRs closely with changing conservation narratives (Bridgewater, 2002; Gavin et al., 2015; Pascual et al., 2021). It is important to understand whether BRs are achieving their three functions, as the periodic decadal reviews set out by *The Seville Strategy* have mixed compliance results (Coetzer et al., 2014; Price et al., 2010; UNESCO, 1996). Thus, developing processes to contribute to compliance monitoring of zonation in the early stages of a BR's lifetime will enable compliance and goal monitoring.

The ecosystem services (ES) concept is a powerful lens through which to understand human–nature relationships (Folke et al., 2011) and can contribute to meeting sustainability targets such as the SDGs (Plieninger et al., 2013; Wood et al., 2018). The ES concept was developed to highlight the importance of biodiversity for human well-being (Ehrlich & Ehrlich, 1981; Westman, 1977) with the intention to secure public interest and support in biodiversity conservation (Gómez-Baggethun et al., 2010). Ecosystem services are now mainstream in the social-ecological literature and becoming evident in policies related to land-use and land planning (Longato et al., 2021; Maes, Egoh, et al., 2012). Translating knowledge to action through policy is an important part of problem-driven research including several areas of ES research (Cowling et al., 2008; Crouzat et al., 2018), and initiatives like the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) have provided impetus for broad-scale consideration of ES. While monetary valuation of ESs has generated political interest in their protection, preservation and enhancement, through initiatives such as Payments of Ecosystem Services schemes (e.g. Muradian et al., 2013; Vatn, 2010), there are very real concerns of nature commodification (Gómez-Baggethun et al., 2010). Moreover, the ways in which people value nature are diverse and often independent of monetary value which to date have been underrepresented in policy and decision-making (Pascual et al., 2017). For just and equitable decision-making, it is therefore important to explore alternatives for ES valuation that are not only dependent on market mechanisms and consider the multiple ways that people value nature (Pascual et al., 2017).

To inform sustainable land-use planning, we need to know how ESs vary quantitatively and spatially across different social-ecological contexts (Cowling et al., 2008; Schröter et al., 2014). The burgeoning field of ES mapping (Burkhard & Maes, 2017) has focussed on regulating and provisioning ES with fewer studies mapping cultural ES (Crossman et al., 2013; Egoh et al., 2012; Martínez-Harms & Balvanera, 2012). Over the past 15 years, there has been a shift in the methodologies and approaches used for assessing and mapping ES, from largely single discipline biophysical and economic methods, towards a higher proportion of pluralistic and socio-cultural methods (Martín-López et al., 2019; Schutter & Hicks, 2021). This methodological shift accompanies the conceptual developments in ES thinking that include the multiple contributions that nature makes to our well-being (e.g. Díaz et al., 2018; Maes et al., 2018; Pascual et al., 2017). Public participation geographical information systems (PPGIS) has emerged as a promising tool for mapping sociocultural ES values (reviewed by Brown & Fagerholm, 2015; Maes et al., 2018), by asking participants to geolocate values for different ES on maps. Cultural, and to a lesser degree provisioning ES are prominent in PPGIS-ES research either due to the ES typology provided to participants (i.e. limited to cultural ES) or because of participant preferences for and/or ability to connect with cultural ES (Brown & Fagerholm, 2015). For example, Scholte et al. (2015) point out that people may not always perceive the capacity of an ecosystem to provide ES because our perceptions are shaped by our interactions with, and knowledge of nature. Therefore, we should expect that non-experts are more likely to values cultural ES which they experience regularly and less likely to appreciate complex regulating ES such as mass flow regulation.

The power of PPGIS to generate spatial knowledge on cultural ES, especially the values that people place on them, is a significant advantage over biophysical ES mapping methods that have been used for cultural ES to date. Spatial distributions of ES values can provide valuable information for planning and management since social acceptance is likely higher when decisions are informed by a wide section of society (Brown et al., 2020). However, there is little evidence that PPGIS has had much impact in real-world planning (Brown & Fagerholm, 2015; Brown et al., 2020). Likewise, the integration of ES in spatial planning remains uncommon (Longato et al., 2021). There are several barriers to the implementation of PPGIS and ES in land-use planning, related to the lack of political will to appreciate the value of local knowledge (Brown et al., 2020). There is therefore a need to find ways to negotiate a place for local knowledge in the political process of land-use planning and allow PPGIS to live up to its promise in planning decision support.

The BR framework and its World Network of BRs can provide an entry point to integrate a PPGIS approach to ES assessments into decision-making. Objective three of the MAB Strategy (UNESCO, 2017) makes clear reference to *sustainability science* defined by them as 'an integrated, problem-solving approach that draws on the full range of scientific, traditional and [I]ndigenous knowledge in a transdisciplinary way to identify, understand and address present and future economic, environmental, ethical and societal challenges related to sustainable development' (UNESCO, 2017, p. 19). This definition underscores the importance of Indigenous and local knowledge, science–society relationships through transdisciplinary processes, and learning and education (Reed, 2020). PPGIS is well suited to MAB objectives related to indigenous and local knowledge on ES because of the strong place-based dimension of that type of knowledge (Raymond et al., 2009). Indeed, a recent report has called for a common protocol for ES assessments in BRs that makes clear recommendations related to broad stakeholder inclusion as well as for the use of maps in stakeholder engagement (Vasseur & Siron, 2019).

Nordhordland UNESCO Biosphere (NBR) in Norway (Kaland et al., 2018) was designated in 2019. This BR is a collaboration between public, private and academic actors and presents an opportunity for baseline transdisciplinary studies on biocultural values, sustainable development and human–nature relationships in NBR. Such studies can contribute to all three aims as set out in the Seville Strategy. We use PPGIS to assess ES values of stakeholders in NBR in a participatory approach engaging key stakeholders to develop the ES typology and then more widely with inhabitants, part-time inhabitants, governance organisations and other key stakeholders to assess spatial distributions of ES values. First, we ask where hotspots of ES values are located within NBR. Second, we ask if there are distinct spatial bundles of ES values in NBR, what those bundles are, where they occur and what are the landscape characteristics associated with them. Third, we compare and contrast the ES values of the designated BR zones. Finally, we reflect on the ES values in relation to zonation in NBR and consider the wider potential for PPGIS in other BRs.

2 | METHODS

2.1 | Study area

Nordhordland UNESCO Biosphere is located on the west coast of Norway covering *c.* 6,698 km^2 stretching from the open Atlantic Ocean and coastal flats in the west, up to the mountains in the east reaching up to 1,313 m a.s.l. at Kleivfjellet (Figure 1). Extensive fjord systems comprise an important component of NBR, including Sognefjorden; Europe's longest, and Norway's longest and deepest fjord (205 km long and 1,308 m maximum depth). Terrestrial land-covers with the greatest areal extents are open and sparse vegetation, and forest along with marine ecosystems in the fjords and open ocean (Figure 1; Table S1).

The climate is a wet-temperate oceanic climate with mean annual precipitation of 2,400 mm and a strong west-east gradient from coast to the mountains; coastal areas receive 1,300 mm precipitation per year while the upland areas receive 3,000 mm. Mean temperatures of the warmest and coldest months are 13.0–14.5°C and 3.0–3.0°C, respectively, in the coastal areas. Temperature variation on the coast is modest with the difference between the warmest and coldest months being 11°C while inland the difference is greater at 16°C.

Employment is predominantly provided by public services while economic activity is dominated by the petroleum industry centred at Mongstad comprising Norway's largest oil refinery and other petroleum businesses. The region is an important provider of hydroelectricity at the national level with production centred in Modalen and Masfjorden municipalities. Although agriculture and fishing are not major economic players, they are nonetheless culturally significant. Aquaculture and fisheries are important industries with large pelagic fish stock and salmon aquaculture which is projected to expand in the future.

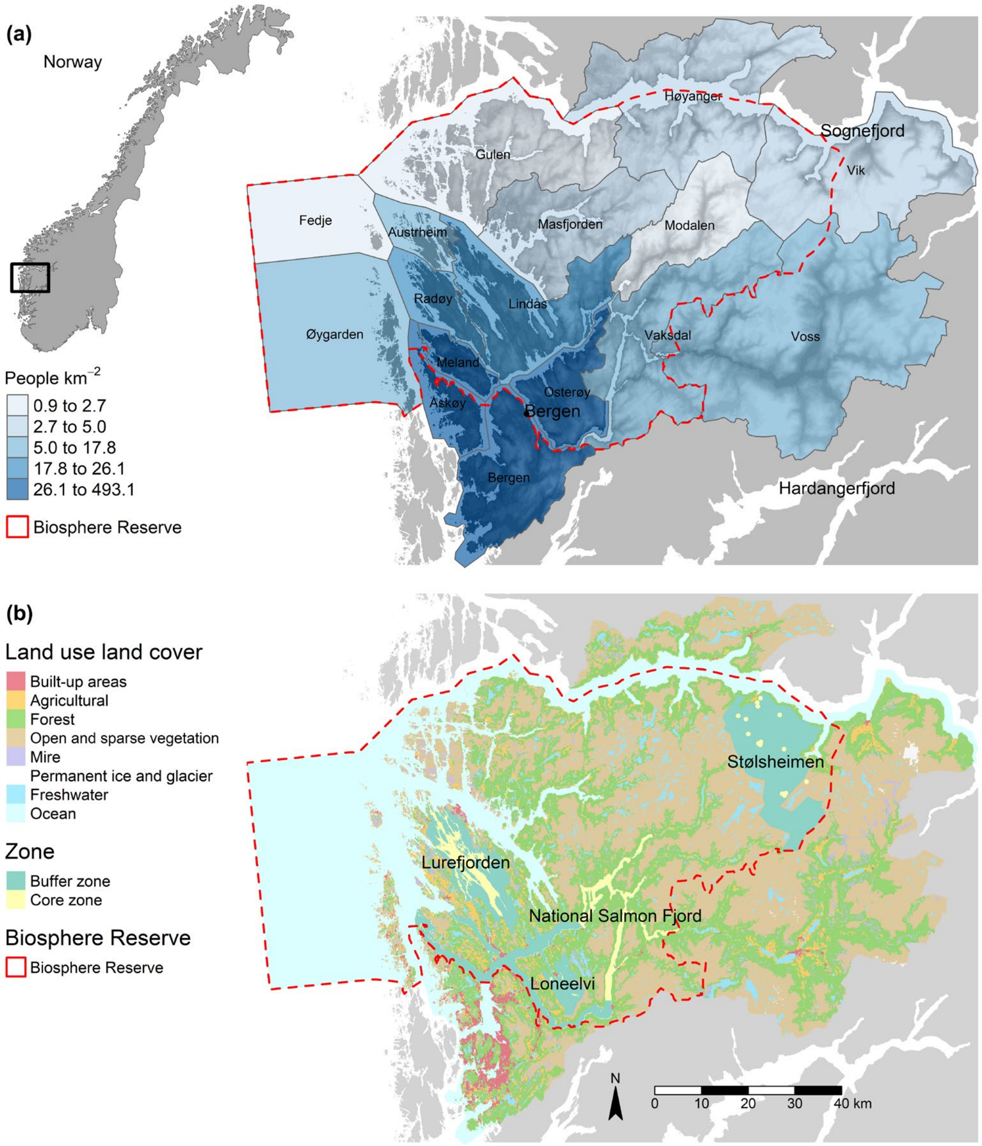

FIGURE 1 (a) Location and population densities of the municipalities and (b) land use-landcover and the location of the different zones and in Nordhordland UNESCO Biosphere on the west coast of Norway

NBR comprises nine municipalities that are contained entirely with its boundaries, with a further five partially within the boundaries (Figure 1). The permanent human population of the nine main municipalities is *c*. 54,000 concentrated in the low-lying south-western coastal areas (Figure 1a) along with an additional *c*. 15,000 seasonal residents comprising predominantly holiday-home owners (Kaland et al., 2018). A further *c*. 332,000 people live in the additional five municipalities, concentrated primarily in Bergen municipality (*c*. 281,190 people).

The zonation of NBR comprises four localities with a core and buffer zone associated with each of those localities (Kaland et al., 2018; Figure 1). The zones represent all the major landscape and seascape in NBR, including the coast and outer archipelago (Lurefjorden), the fjord landscape (National Salmon Fjord and Loneelvi River) and the mountain landscape (Stølsheimen; Figure 1). Each locality has its own unique characteristics encompassing the breadth biocultural diversity found in NBR including cultural heritage monuments and upland summer farms at Stølsheimen, agricultural and cultural landscapes in the buffer zones of Loneelvi and Lurefjorden, and important biodiversity and research sites in the core areas of Lurefjorden and the National Salmon Fjord.

2.2 | Survey design and ecosystem services typology

The ES typology and survey design was developed in three steps. First, we used the NBR UNESCO application document (Kaland et al., 2018) to identify locally relevant ES. Second, we used published literature on ES value mapping to identify ES not already included in the NBR UNESCO application document referring specifically to recent PPGIS-ES studies to guide the ES statements in the survey. The statements for each ES were based on previously published PPGIS-ES studies (e.g. Fagerholm et al., 2016, 2019; Plieninger et al., 2019) capturing the use and subjective perceptions components of socio-cultural values of ES (cf. Scholte et al., 2015). Finally, we used a workshop with local stakeholders to test the survey and typology asking whether the ES identified by us were perceived as relevant to them, or if there were any ES we had missed, and if the statements in the survey were interpretable by them. We assembled a stakeholder group facilitated by an existing relationship between NBR's coordinators, municipalities and scientists. The stakeholder group included local food producers (2), municipality planners (3), agricultural advisors (2) and members of the NBR working group (2). Two of the participants were both farmers and agricultural advisors. The final typology comprised 12 ES (Appendix 1). We have in general attempted to link the ES to the Common International Classification of Ecosystem Services (CICES; Haines-Young & Potschin, 2018). However, we modified both the typology and ES statements, so they were locally relevant and understandable to non-experts based on feedback obtained during the focus group. Thus, our ES statements and typology is a balance between a commonly accepted ES typology and interpretability for local stakeholders. Two of our ES, 'hunting and fishing' and 'wild plants, berries and mushrooms for food' can be classified as cultural and as provisioning ES since both provide food and are linked to social interaction, recreation and cultural traditions (Stryamets et al., 2015; Vári et al., 2020). However, we have considered these as cultural ES which is consistent with the socio-demographics of NBR and other studies in similar contexts (Malmborg et al., 2021; Meacham et al., 2016; Quieroz et al., 2015; Stryamets et al., 2015).

2.3 | Data collection

We used a web-based PPGIS survey in Maptionnaire (Mapita Oy, 2019, https://app.maptionnaire.com/en/6998/) to collect ES values in NBR. Survey participants were recruited through various methods including targeted email lists comprising local actors from organisations involved in resource management, local and regional government, agriculture, nature conservation, forestry and energy production; articles about the project and survey in one regional newspaper and two local newspapers; boosted social media adverts; and promotions on the NBR social media accounts. We encouraged key actors to share the survey through snowballing. In addition, we organised 18 workshops at local libraries and community halls in 12 municipalities between 10 February and 13 April 2020 (Table S2). The final four workshops scheduled after 11 March were cancelled due to COVID-19 restrictions. The restriction meant that there was one municipality entirely within, and one partially within NBR that we could not hold a workshop. Workshop participants were recruited using advertisements by posting flyers with the schedule on municipality webpages, library noticeboards and newspaper listings. At the workshops, a short presentation about the project was given, allowing for questions from participants, followed by an opportunity for attendees to take the survey on laptops provided by us. We provided guidance on functionality and clarified questions that participants had. The total number of participants at the 14 workshops we were able to hold was 30 ranging between zero and eight (median 2). See Table S2 for more details of workshop attendance.

The survey was open from 3 February to 2 June 2020. Participants mapped points related to ES within our typology and were able to map as many or as few points as they chose; we recommended between 10 and 20 points. In addition, we asked participants to provide socio-demographic information. Ethics approval was obtained from The Norwegian Centre for Research Data (Naturgoder i Nordhordland UNESCO Biosfæreområde, Ref no. 657151). All participants gave consent in accordance with the conditions approved by The Norwegian Centre for Research Data prior to filling out the survey.

2.4 | Analyses

2.4.1 | Hotspot analysis

We used kernel densities to represent and visualise hotspots of ES categories mapped by participants: provisioning, cultural and regulating (Brown et al., 2015; Hausner et al., 2015). Kernel density estimates were calculated in R (R Core Team, 2020) using the *sp.ke* function in the SPATIALECO package (Evans, 2020) using a cell size of 100 m and an appropriate bandwidth for each ES category (Brunsdon & Comber, 2019). We used nearest neighbour (NN) ratios to test for clustering in each ES category calculated with the *nni* function in SPATIALECO (Evans, 2020).

2.4.2 | Ecosystem service bundles

We assessed bundles of ES values—groups of repeatedly co-occurring ES (Raudsepp-Hearne et al., 2010)—at a grid scale. There is no 'perfect cell size' for determining bundles so we chose 500 m as it was large enough to capture multiple points per cell and closest to the most similar study of this type (Plieninger et al., 2019). We calculated the cell point-densities of each ES, removed all cells that contained zero mapped points and used principal component analysis (PCA) to reduce the dimensionality of the data (Brown et al., 2015; Plieninger et al., 2019). We selected the number of components that explained at least 65% of the variance and applied varimax rotation (Brown et al., 2015; Plieninger et al., 2019; Zoderer et al., 2019). The best number of clusters was determined using hierarchical clustering on the factor loadings with the 'NbClust' function in NBCLUST package (Charrad et al., 2014) setting the distance measure to 'euclidean', the method to 'ward.D', the index to 'alllong' and the Beale's index ('alphaBeale') to a significance value of 0.1 (Madrigal-Martínez & Miralles i García, 2020). Cells were then assigned to clusters using 'hclust' and 'cutree' functions (R Core Team, 2020). Finally, we calculated the mean number of points of each ES value per grid cell per cluster and visualised them with flower petal diagrams in GGPLOT2 (Wickham, 2016).

2.4.3 | Maximum entropy modelling

We used maximum entropy (MaxEnt) modelling to assess the importance of spatial landscape characteristics in determining the distribution of mapped ES-value bundles. MaxEnt modelling is used widely in ecology and biogeography for species distribution models (SDMs) and is increasingly used in modelling ES and landscape values from PPGIS surveys (e.g. Muñoz et al., 2020; Sherrouse et al., 2011, 2014). We selected 10 variables at a resolution of 500 m (distance from roads, buildings, and hiking trails, percentage cover of agricultural land, water, forest and open LULC types, and elevation, slope, and richness of LULC, see Table S3 & Figure S1) for the models based on previous studies (Bagstad et al., 2017; Muñoz et al., 2020; Sherrouse et al., 2014) and additional variables considered to be important social-ecological drivers of ES values in NBR. Modelling was performed with the 'maxent' function in the DISMO R package with withholding 20% of the points for model evaluation and 10,000 background points (Hijmans et al., 2020). Models were evaluated using area under the receiver operator curve (AUC) in which we considered scores of 0.5–0.7, 0.7–0.9 and 0.9 poor, moderate and excellent model performances, respectively. We compared predicted distributions of the bundles using 'calc.niche.overlap' with ENMTOOLS (Warren & Dinnage, 2021) which computes the overlap in predicted distributions ranging from 1 (identical distributions) to 0 (no overlap at all).

2.4.4 | Ecosystem service values and Biosphere Reserve zonation

We overlaid the PPGIS points with the different zones and counted the number of points for each ES value in each zone to assess stakeholders' ES values. Before overlaying the points, we created a polygon buffer of 10 m around each point to account for mapping precision inaccuracies (Fagerholm et al., 2019). We chose a smaller buffer than used in other studies to avoid too much overlap between terrestrial and aquatic values. Flower petal plots were used to visualise the relative differences in the proportion of ES values mapped within the whole of NBR, the three main zones and among the specific zones.

3 | RESULTS

3.1 | Socio-demographics of participants

The proportion of respondents per municipality was different to the proportion of the general population ($X^2 = 105.79$, $p < 0.001$, Table 1). There was an over representation of participants in the smaller municipalities with smaller populations, including Fedje, Masfjorden and Modalen (X^2 residuals = 4.43, 2.51 and 7.76, respectively) and an underrepresentation in Osterøy (X^2 residual = −2.95). The respondents were also typically older and had higher levels of education than the population in NBR (age: $X^2 = 350.71$, $p < 0.001$; education: $X^2 = 74.66$, $p < 0.001$; Table 1). There was no difference in sex representation between the sample and the population of NBR and in general respondents reported high levels of regional knowledge (Table 1).

3.2 | Mapped ecosystems services

Overall, 433 study participants mapped 3,155 individual points linked to ES values in NBR. Cultural ES values were the most mapped category (2,277 points), followed by provisioning (524 points) and regulating (354 points, Figure 2). Outdoor recreation was the most mapped (768 points) followed by appreciation of biodiversity (366 points). Protection for extreme events/weather, energy and climate change mitigation were the least mapped (51, 81 and 106 points, respectively).

3.2.1 | Biosphere Reserve zones

Mapped ES values within the transition zone were almost identical to those mapped across the whole of NBR (Figure 2). The buffer and transition zones differed only slightly with moderately higher agricultural and cultural heritage values in the buffer zone. There was, however, a marked difference between the core, and the buffer and transition zones with hunting and fishing, and clean air, water and soil values being higher in the core zone than the other two zones. Furthermore, agricultural values were largely absent from the core zone.

There were noticeable differences in mapped ES values between adjacent buffer and core zones aside from in the Stølsheimen area. Here, both the core and buffer zones were dominated by outdoor recreation values with relatively low frequencies of other ES values. The two buffer zones that are adjacent to aquatic core zones (i.e. Lurefjorden and Loneelvi) had high agricultural and outdoor recreation values. Lurefjorden buffer zone also had high cultural heritage values. All three zones located within marine environments (i.e. Lurefjorden core, Salmon fjord core and buffer) had high fishing values.

Values for all three ES categories were significantly clustered, although cultural ES more so than regulating and provisioning (Figure 3; Cultural—NN = 0.605, z-score = −36.0, p-value = 0.001, Provisioning—NN = 0.587, z-score = −18.1, p-value = 0.001; Regulating—NN = 0.710, z-score = −10.4, p-value = 0.001). In general, hotspots of all ES categories were associated with areas of high population densities closer to settlements in the low-lying coastal areas on the western side of NBR (Figure 3).

3.3 | Ecosystem service bundles and maximum entropy modelling

The PCA analysis identified seven factors that explained 66.6% of the variance with factor loadings. Hierarchical cluster analysis of the first seven varimax rotated PCA scores identified five distinct bundles of perceived ES at the grid scale (Figure 4). We classify these as

TABLE 1 Socio-demographics of survey participants and population. Numbers in the 'Study' column represent the number of respondents and percentages relative to total survey respondents, while number in the 'Population' column represent numbers and percentages of inhabitants in relation to the whole study area as reported in census data

	Study		Population[a]	
Variable	***n***	**%**[b]	***n***	**%**
Municipality lived in				
Austrheim	10	3.1 (4.6)	2,393	5.5
Fedje	10	3.1 (5.7)	473	1.1
Gulen	9	2.8 (4.2)	1,947	4.5
Lindås	83	25.8 (31.4)	12,722	29.2
Masfjorden	15	4.7 (9.2)	1,402	3.2
Meland	29	9.0 (12.4)	6,318	14.5
Modalen	12	3.7 (2.1)	300	0.7
Osterøy	19	5.9 (8.1)	6,577	15.1
Øygarden	17	5.3 (6.4)	3,906	9.0
Radøy	30	9.3 (11.7)	4,171	9.6
Vaksdal	11	3.4 (4.2)	3,326	7.6
Does not live in the region	77	23.9 (—)	—	—
Education				
Less than a high school diploma	11	3.4	72,236	22.8
High school diploma or similar	83	25.8	112,428	35.5
Bachelor or technical degree	121	37.6	91,928	29.0
Master's and PhD degree	101	31.3	38,609	12.2
Not answered	6	1.9	—	—
Sex				
Female	151	46.9		49.7
Male	156	48.4		50.3
Other	3	0.9	—	—
Prefer not to answer	8	2.5	—	—
Not answered	4	1.2	—	—
Mean age	50.4		45.7	
Age range				
15–24	17	5.3		15.5
25–34	26	8.1		14.1
35–44	50	15.5		15.3
45–54	73	22.7		16.4
55–64	80	24.8		14.9
≥64	53	16.5		23.8
Not answered	23	7.1		—
Self-reported regional knowledge[c]				
0–20	5	1.6	—	—
21–40	6	1.9	—	—
41–60	26	8.7	—	—
61–80	87	27.0	—	—
81–100	179	55.6	—	—
Not answered	17	5.4	—	—

[a]Census data from Statistics Norway (2019c).

[b]Number in parentheses denotes the municipality that respondents know the best and includes respondents who do not reside in Nordhordland UNESCO Biosphere.

[c]Knowledge of the entire region was reported by participants on a sliding scale between zero and 100.

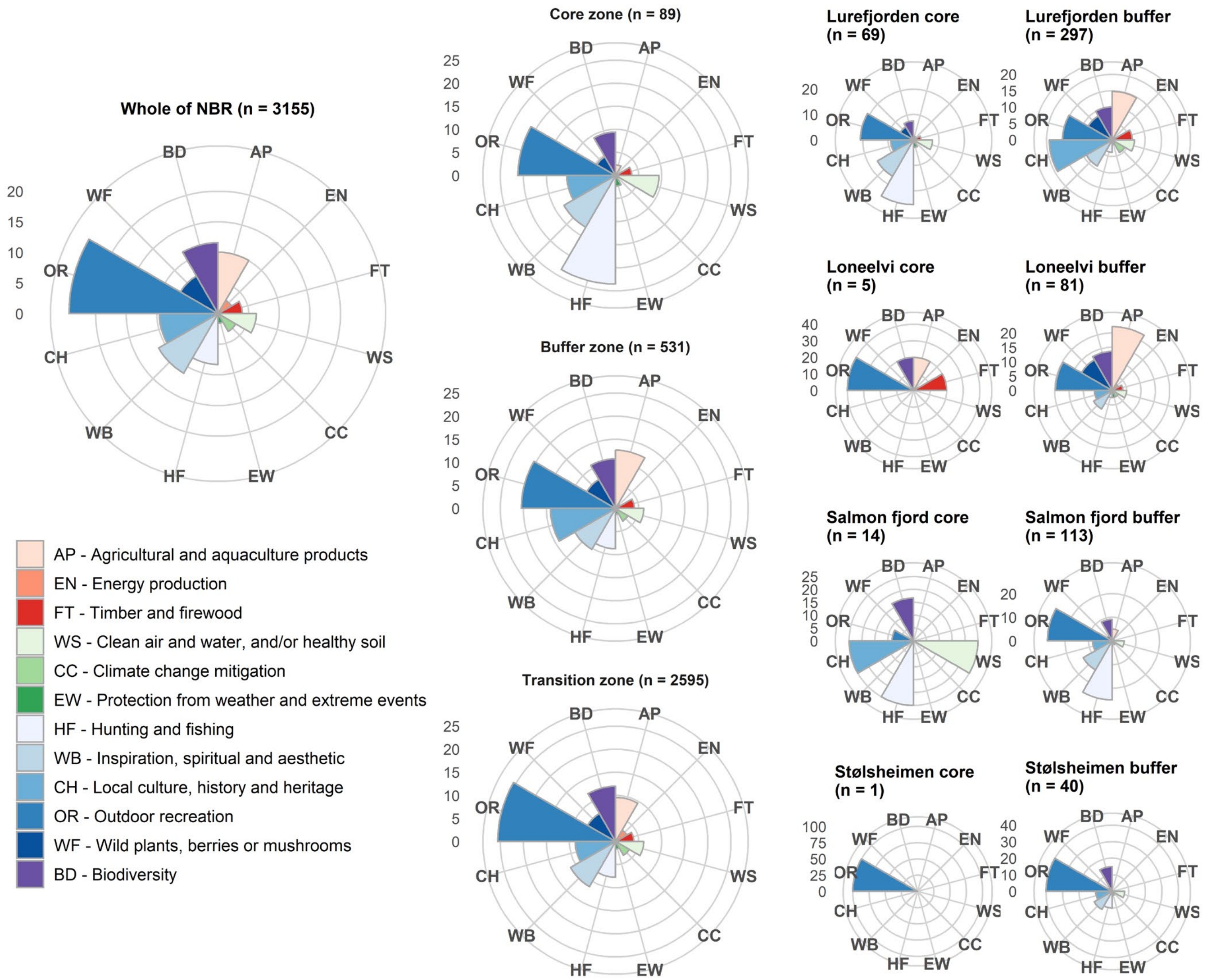

FIGURE 2 Proportion of points mapped for each ecosystem service (ES) value in the PPGIS in the whole of Nordhordland UNESCO Biosphere (NBR), the three biosphere zones and the specific zones. Petals are the percentage of points mapped per ES value within each zone and represent differences in ES values within each petal diagram

follows: 'passive cultural values' (Bundle 1, n = 369 cells), characterised by predominantly well-being and non-animal wild food values; 'multifunctional landscapes' (Bundle 2, n = 229 cells), characterised by a relatively even spread of ES values although a higher proportion provisioning relative to other ES classes; 'cultural landscapes' (Bundle 3, n = 372 cells), dominated by agriculture and cultural heritage values; 'active outdoor recreation' (Bundle 4, n = 872), characterised by dominance of outdoor recreation values, and to a lesser degree biodiversity values; and 'wild animal resources' (Bundle 5, n = 216 cells), dominated by hunting and fishing (Figure 4). The points in each bundle were spatially clustered, although to varying degrees. The points in 'multifunctional landscapes' was the most clustered (NN ratio = 0.34, z-score = 31.83), while the 'passive cultural values' was the least clustered (NN ratio = 0.73, z-score = −11.03).

The probability distributions from the MaxEnt models were generally similar in that highest probabilities tended to be located to the west and along the fjord coastlines (Figure 4). However, there were also clear differences in the probability distributions among the bundles. The 'passive cultural values' and 'outdoor recreation' bundles were the most similar (niche overlap = 0.895) with widely distributed, and higher distribution probabilities further inland and at higher elevations than the other bundles. The other three bundles were more restricted in their distributions with 'multifunctional landscapes' and 'cultural landscapes' being most similar (niche overlap = 0.832) and concentrated in the coastal strandflat and along the fjords. The 'wild animal resources' bundle distribution was least like all other bundles being least similar to 'cultural landscapes' (niche overlap 0.678) and most similar to 'active outdoor recreation (niche overlap 0.720), with moderate to high probability distributions in the marine environment within the fjords, and in freshwater lakes and rivers.

Topography (elevation and slope), motorised access (distance to roads) and settlements (distance to buildings) generally contributed the most to the MaxEnt models (Figure 5). Elevation, distance to roads, LULC richness and agricultural land were most important

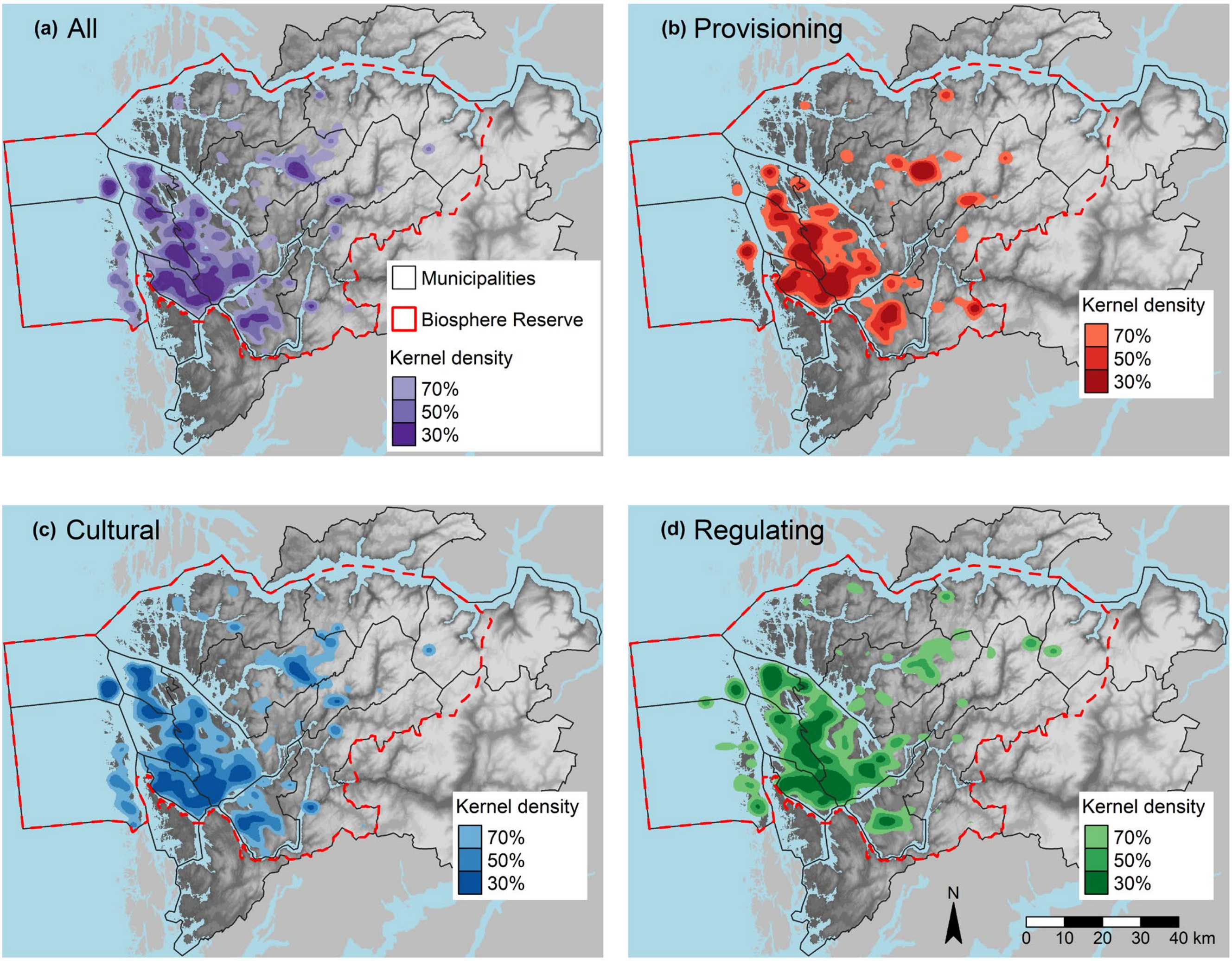

FIGURE 3 Hotspots of mapped (a) all, (b) provisioning, (c) cultural and (d) regulating ecosystem service categories in Nordhordland UNESCO Biosphere. Isopleths represent 30%, 50% and 70% of the mapped points for respective ecosystem service categories

for the passive cultural values. Motorised vehicle access, agricultural and forested land, and LULC richness were most important for the multifunctional landscapes. Distance to buildings and agricultural land were most important for the cultural landscapes bundle. Elevation, and to lesser degree distance hiking trails and buildings, and slope were important for the active outdoor recreation bundles. Distance to buildings and to a lesser degree motorised access trail, and cover of water and open land were most important for the wild animal resources bundle. Models performed moderately well with AUC scores > 0.79 for all bundles (passive cultural values = 0.81; multifunctional landscapes = 0.88; cultural landscapes = 0.86; outdoor recreation = 0.79; wild animal resources = 0.81).

4 | DISCUSSION

As places for fostering biocultural diversity and understanding the multiple connections between people and nature, BRs constitute model systems for the implementation of participatory methods for ES valuation. Our study highlights the importance of outdoor recreation, biodiversity, cultural heritage, mental well-being and agricultural values to stakeholders in NBR, and that these values tend to be highest close to where people live. We show that ES values differ in the different BR zones reflective of zonation goals, most prominently higher values for cultural and regulating services, and low values for provisioning services, in core relative to other zones. We also identify commonly co-occurring ES values, or bundles, in NBR along with the landscape characteristics that determine the spatial distribution of those bundles.

4.1 | Biosphere reserves as biocultural landscapes of people and nature

Participants in NBR mapped substantially more cultural ES values than the two other ES categories. This predominance of cultural ES

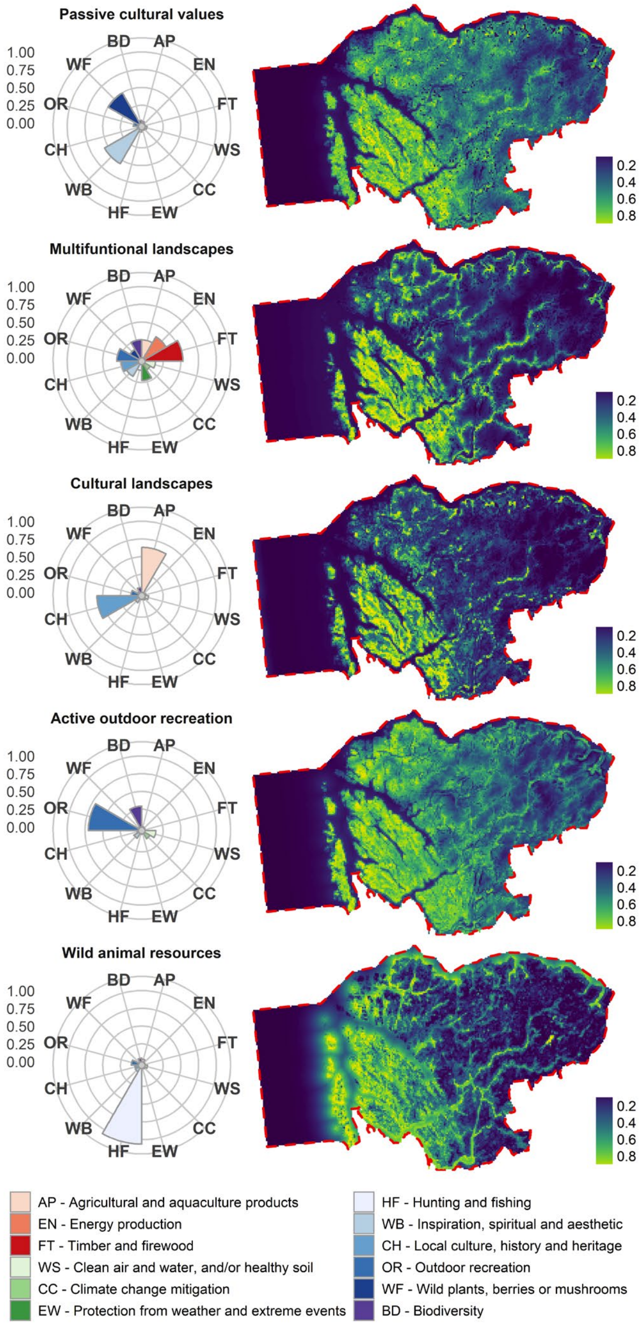

FIGURE 4 The five bundles of ecosystem service (ES) values and the MaxEnt probability surface of those clusters in Nordhordland UNESCO Biosphere. Grid cells are 0.25/km^2 and petals represent the mean number of points per 0.25/km^2 grid cell for each ES in the clusters

values is a distinctive feature of PPGIS-ES studies and the European context (e.g. Brown et al., 2012; Fagerholm et al., 2016, 2019; Raymond et al., 2009). Likewise, the low frequency of regulating ES values is also a typical characteristic of such studies. While it is acknowledged that there were more choices for cultural ES (five) than other categories (three or fewer), this is insufficient to explain the dominance of mapped cultural ES. The ability to connect with well-being associated with place-based outdoor recreation (e.g. exercise) is an important factor determining how ES are likely to be valued, resulting in higher mapping frequency for cultural ES values (Brown, 2012). This is a strength of the PPGIS method since mapping cultural ES is challenging using biophysical indicators (e.g. viewshed analysis, hiking trail density) or social media data (e.g. georeferenced social media photographs; Crossman et al., 2013). Thus, PPGIS combined with modelling approaches such as MaxEnt greatly advances the capacity to map cultural ES.

Stakeholders in NBR value places for outdoor recreation significantly more than any other ES values. Indeed, high values for outdoor recreation is also consistent with other similar studies in Europe (Baumeister et al., 2020; Fagerholm et al., 2016, 2019) and within Norway (Brown et al., 2015; Hausner et al., 2015; Muñoz et al., 2020). The deep connection that Norwegians have with outdoor recreation is a fundamental part of the cultural identity that is written into law though *Allemannsretten* (everyman's right/freedom to roam) in the Outdoor Recreation Act (Klima- og miljødepartementet, 1957) allowing freedom of access to all land apart from cultivated land. People that exercise outdoors choose to do so for many reasons, but convenience and experiencing nature have been identified among the most important factors that influence that decision in Norway (Calogiuri & Elliott, 2017). Furthermore, exercise has clear physical well-being benefits though for example improved cardiovascular function, but there is also evidence that species and ecosystem diversity have positive mental well-being benefits (Aerts et al., 2018). Thus, our 'active outdoor recreation' bundle which includes biodiversity values is consistent with the mental and physical well-being co-benefits of recreation and biodiversity and further supports the biocultural conservation paradigm of biosphere reserves (Bridgewater, 2002). Through our work, we also highlight the importance of increasing the uptake of participatory methods that reflect these kinds of nature values into landscape and urban planning.

Our novel use of MaxEnt to explain the spatial distribution ES value bundles of diverse stakeholders provides further insight into the landscape characteristics influencing accessibility to those bundles. We find that specific landcover types had little influence on the distribution of the 'active outdoor recreation' and 'passive cultural values' bundles suggesting that different landcovers are equally valued for both 'active' and 'passive' recreation. Rather the distributions of these two bundles are determined largely by physical accessibility in the form of topography, road and trail access, and travelling distances from settlements, and in the case of 'passive cultural values', landscape configuration (i.e. LULC richness). This is consistent with *Allemannsretten* since there are few legal restrictions to movement (Hausner et al., 2015) and contrasts somewhat with the findings Fagerholm et al. (2016) who also found low preferences for LULC but disproportionately high number of mapped ES in small areas of common land in Spain where land access is more restrictive. Accessibility has been identified by other PPGIS studies as important in determining where participants map ES values (Fagerholm et al., 2016, 2019; Muñoz et al., 2020; Plieninger et al., 2019). Indeed, accessibility is

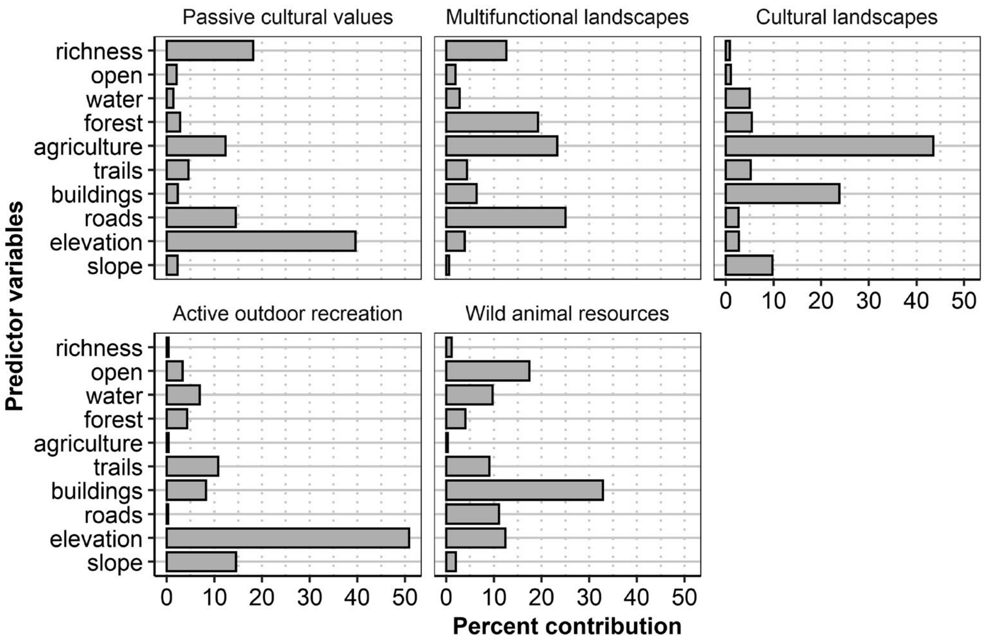

FIGURE 5 Variable contribution (%) of the 10 variables to the MaxEnt models for each of the five bundles in Nordhordland UNSECO Biosphere

increasingly important for biophysical mapping of cultural ES such as recreation (Ala-Hulkko et al., 2016; Paracchini et al., 2014). We infer that travelling time and accessibility as determined by infrastructure are likely to be more important for recreation choices than LULC type (Paracchini et al., 2014).

4.2 | Agriculture and cultural heritage are inseparable

Values for provisioning services were dominated by agricultural products reflecting the rural farming landscape of NBR while other provisioning ES were poorly represented in mapped ES values. The 'cultural landscapes' bundle captures both agricultural and cultural heritage values and represents a synergy between these ES values of respondents, adding to the recurring theme of the biocultural values of the region. Plieninger et al. (2019) report a similar bundle from their PPGIS study. Our results go further and highlight that values for agriculture and cultural heritage as assigned by a diverse group of stakeholders are largely inseparable. We interpret this as the cultural landscape of agriculture (*jordbrukets kulturlandskap*) strongly associated with agricultural sector discourses (Jones & Daugstad, 1997). The strong ties with these kinds of places can be understood by recognising that landscapes are places that have developed through human interactions with nature including cultural and social practices (Olwig, 2007). In the context of NBR, agricultural and cultural heritage ES values embody this landscape perspective due to the long history of agriculture and the strong interconnection between farming and culture in NBR (Kaland et al., 2018). The social-ecological system of western Norway has developed over millennia through the creation and maintenance of the cultural landscape from agricultural activities of grazing, mowing and burning (Hjelle et al., 2006; Webb, 1998). Human–nature relationships in the region are therefore strongly agrarian and linked to the agricultural and semi-natural ecosystems (e.g. heathlands and hay meadows) shaped by people. These semi-natural ecosystems associated with agriculture such as coastal heathland and hay meadows support high species diversity, numerous iconic species (e.g. *Hubo hubo*), keystone species (e.g. *Calluna vulgaris*), contain around 24% of all Red Listed species in Norway (Henriksen & Hilmo, 2015), and the ecosystems themselves are Red Listed (Artsdatabanken, 2018). Although biodiversity values were not bundled together with agricultural and cultural heritage ES values in our analysis, there is still a synergistic relationship between biodiversity and many other ES in certain agricultural land-use types in western Norway (Johansen et al., 2019; Wehn et al., 2018). In this we can see overlapping values of the discourses of the agricultural sector's cultural landscape of agriculture and those of the nature conservation sector's interpretation of the cultural landscape (Jones & Daugstad, 1997). Thus, from our results, we can conclude that in the context of NBR, conservation of cultural landscapes can have multiple ES benefits by preserving cultural, agricultural and biodiversity values (Linnell et al., 2015).

Our MaxEnt modelling shows high contributions of agricultural landcover and distance to buildings to the distribution of the cultural landscapes bundle. This shows the strong place-based dimension of cultural landscapes in NBR which has important implications for managing land-use change in rural settings in Norway and likely elsewhere in Europe. Like other parts of Europe with moderate-to-low agricultural production, there is a trend of agricultural land abandonment driven by factors such as low profitability for farmers and reductions in access to infrastructure (Beilin et al., 2014). Therefore, the loss of agricultural practices will not only reduce agricultural ES, but also erode cultural heritage values of the region. In the Norwegian context, farmers often perceive their roles in both food production and maintenance of cultural landscapes (Bernués et al., 2015, 2016; Kvakkestad et al., 2015). Part-time farmers and other stakeholders in Norway are more interested in maintenance of cultural heritage and landscapes than full-time farmers (Bernués et al., 2015; Kvakkestad et al., 2015). However, full-time farmers have greater interest in payments for food production rather than public goods associated with cultural landscapes (Kvakkestad et al., 2015). In this context, it is likely that policies aimed at maintaining diverse mixed agricultural jobs (i.e. part time and full time) will provide social-ecological resilience against drivers of change that affect linked cultural heritage and agricultural values.

The diversity of ES values in the multifunctional landscapes bundle is distinctive among the bundles and similar to 'Ecosystem Services hotspots' reported by Plieninger et al. (2019), as is the importance of roads and settlements in determining their distribution. We found that forested land and agricultural land as well as landscape configuration (LULC richness) were important contributors further supporting the multifunctionality of this bundle, including firewood and timber, and agricultural ES values. Importantly, ES values mapped by participants do not necessarily reflect the potential of an area to supply ES, but rather more specifically their place-based values, and in the case of cultural ES, their actual supply. This tendency of higher densities of ES values mapped closer to settlements can likely be attributed to geographical discounting (people choose to be close to the things they value on the one hand but prefer to be more distant from what they have an aversion to on the other; Brown & Kyttä, 2014), highlighting the importance of nature close to where people live for ES delivery and well-being (Fagerholm et al., 2016, 2019). In the regional context of urbanisation, spatial data produced by a diverse group of local actors demonstrating the multiple benefits that the community gets from nature near urban and peri-urban areas can provide useful information for prioritisation in urban expansion planning.

4.2.1 | Biosphere Reserve zonation and the new generation of Biosphere Reserves

The ES values mapped by stakeholders in the different zones in NBR reflect the new generation of BRs, with biocultural values well represented in the buffer and transition zones, including biodiversity, agricultural and cultural heritage (Coetzer et al., 2014; Price, 2017; Winkler, 2019). The terrestrial buffer zones in NBR have proportionately higher agricultural land than the transition zone (see Table S3) which explains the high agricultural values in the buffer zone. Importantly, agricultural practices in NBR are predominantly on small holdings (<14 ha) with low intensity livestock farming at relatively low stocking densities in a highly heterogeneous landscape with mixed LULC types (<1 livestock unit per hectare; Statistics Norway, 2019a, 2019b, 2019c). Thus, high values for agricultural ES as well as biodiversity values is consistent with ecologically compatible practices intended for BR buffer zones. However, although the agricultural practices can be considered relatively ecologically compatible at the local scale, agricultural intensification may lead to less ecologically favourable practices such as high nutrient inputs or the use of imported soy-based powerfeed resulting in telecoupled environmental impacts (Hull & Liu, 2018; Schaffer-Smith et al., 2018). The relative absence of extractive values in the core zones, aside from recreational fishing, and a higher presence or regulating and cultural values, is also consistent with BR aims for biodiversity conservation and reduced human impact in core zones that does not prohibit human presence (Winkler, 2019).

Our study is the first, to our knowledge, that uses a participatory and transdisciplinary approach to investigate spatial distributions of ES values in relation to BR zonation. Importantly, transdisciplinary participatory processes in BRs have been shown to result in multiple benefits including enhanced social learning, facilitate relationships among actors and improve the understanding of varying perspectives among actors (Onaindia et al., 2013). Our assessment of ES values in NBR touches on several important issues related to BRs. First, the ES concept fits well within the BR focus on human–nature relationships and our approach of spatial assessment of ES values has rarely been undertaken in BRs. There are few studies that have mapped ES in biosphere reserves (but see Kermagoret & Dupras, 2018; Poikolainen et al., 2019), and even fewer that explicitly consider zonation in their analyses (but see Castillo-Eguskitza et al., 2018, 2019). Second, we have used a participatory approach which is an important criterion of BR governance. Indeed, participatory processes may be one of the most important in supporting the goals of BRs and contribute towards the other goals (Schultz et al., 2011). Such methodology is key to the aims of BRs and is an important step in addressing sustainability and equity challenges faced within BR territories (Barraclough et al., 2021; Hill et al., 2020; IPBES, 2019). Third, our work constitutes the first empirical investigation into the alignment between a BR zonation plan and the values BR inhabitants place on a landscape, providing an understanding of the potential mismatches between zonation theory and implementation (Mehring & Stoll-Kleemann, 2011).

The five spatial bundles we find in NBR are highly distinctive, with values for one or two ES dominating each bundle aside from the 'multifunctional landscapes' bundle. This contrasts with biophysical ES bundle studies in which bundles tend to have several co-dominant ES and mirrors the results of a similar study by Plieninger et al. (2019). Our results also confirm that there are more synergies in PPGIS-ES compared to biophysical ES bundling studies that typically find less synergy between provisioning and cultural ES (e.g. Crouzat et al., 2015; Maes, Egoh, et al., 2012; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Turner et al., 2014). However, trade-offs between cultural and provisioning ES are not universal in all biophysical studies (e.g. Malmborg et al., 2021) and other socio-cultural studies have found agricultural and cultural heritage ES values do bundle together (Quintas-Soriano et al., 2019; Zoderer et al., 2019). A combination of biophysical and social-cultural methods is likely to yield a more holistic picture of ES values in a region, expanding the knowledge base for land-use planning and management (Bagstad et al., 2017; Scholte et al., 2015).

Lastly, we find energy production being mapped at the second lowest frequency of all ES values to be a striking finding. This is surprising given that Vestland is the highest energy producing county, predominantly hydroelectricity, in Norway. Many hydroelectricity generators are located in areas with low population density and thus their value might not be reflected in our results because people tend to map values for ES closer to home (Fagerholm et al., 2016). Another possible explanation is the land-use conflicts with energy production (hydro and wind) in NBR arising from the impacts that energy production has on biodiversity, visual aesthetics, recreation and cultural heritage (Bakken et al., 2012; Idsø, 2017; Saha & Idsø, 2016). Furthermore, there are major plans to expand wind electricity generation in the region which have been met with opposition from many groups. Brown and Raymond (2014) propose methods to use PPGIS for identifying conflicts in land-use planning whereby participants map landscape values along with development preferences. Our study points towards the need for further work using PPGIS to investigate the potential conflicts between land-uses like power generation and other ES values, particularly in the context of human–nature coexistence and management of BRs as multifunctional landscapes.

5 | CONCLUSIONS

Biosphere reserves (BR) are key learning sites or model regions for sustainable development. Our novel use of PPGIS to explore the spatial distribution of ES in relation to BR zonation shows that stakeholders clearly identify ES values that are broadly representative of BR zonation goals. Buffer zones have high biocultural values linked to outdoor recreation, cultural heritage, biodiversity and agricultural products, while ES values for agricultural products were absent from in core zones. These combinations of ES values in the different zones as perceived by a diverse range of stakeholders show how a modern BR reflects the key goal of biocultural conservation. Furthermore, we show that PPGIS is a valuable means to assess the ES values in BR zones that can be used for BR monitoring. Our bundling approach combined with MaxEnt modelling highlights important ES values related to agriculture and cultural heritage, recreation and biodiversity, and the importance of accessibility to nature for ES provision. First, stakeholders identify a strong link between agriculture and cultural heritage reflecting the long history of farming in the region that remains fundamental part of the local identity. Our demonstration of linked agricultural and cultural heritage values in agricultural areas complements existing knowledge of notable biodiversity and high ES provision in western Norway's agricultural landscapes. Thus, a reduction of agricultural practices will not only reduce agricultural ESs, but also erode cultural heritage ES values and contribute to biodiversity loss, and policies aimed at maintaining key agricultural landscapes provides social-ecological resilience against drivers of change that affect linked cultural heritage and agricultural values. Second, we find high values for outdoor recreation in our study which often co-occur with biodiversity values. This finding emphasises the importance of mental and physical co-benefits that people receive from nature-based recreation. Third, accessibility of nature strongly influences ES values and people map more ES values closer to human infrastructure. Accessible and healthy nature close to home is therefore important to support physical and mental well-being. The transdisciplinary approach of our study facilitated by NBR gives an entry point for a multidirectional flow of knowledge between local actors, municipalities and academia. The development and strengthening of existing relationships can play a key role in BR success (Bridgewater, 2016), and the incorporation of multiple knowledge systems can contribute planning support and shared visioning (Pretty, 2011; Tengö et al., 2014). Perhaps most importantly, planning decisions based on shared visions are likely to have the greatest community backing (Brown et al., 2020) and, in the case of multifunctional landscapes, support sustainable management and supply of locally relevant ES (García-Llorente et al., 2012).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

J.C., A.M.D.B. and I.E.M. conceived the ideas for this study; J.C. and A.M.D.B. designed the PPGIS survey, facilitated the focus group session and administered the PPGIS survey for data collection; J.C. performed all data manipulations and analyses and wrote the first manuscript draft; A.M.D.B. and I.E.M. contributed significantly to review and editing of the draft manuscript.

DATA AVAILABILITY STATEMENT

PPGIS data used in this study are deposited in the Dryad Digital Repository https://doi.org/10.5061/dryad.5hqbzkh6v (Cusens et al., 2021). All other data sources are listed in Supporting Information.

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SUPPORTING INFORMATION

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Supporting Information

Participatory mapping reveals biocultural and nature values in the shared landscape of a Nordic UNESCO Biosphere Reserve

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SUPPORTING INFORMATION

Table S1. Proportion of different LULC types within each zone in Nordhordland Biosphere Reserve.

LULC	**All NBR**	Transition Zone	Stølsheimen		Salmon Fjord		Loneelvi		Lurefjorden	
			Buffer	Core	Buffer	Core	Buffer	Core	Buffer	Core
Cultivated soil	2	1	0	0	0	0	11	0	9	0
Infield pasture	1	1	0	0	0	0	10	0	8	0
Conifer forest	9	9	0	0	0	0	14	0	29	0
Broadleaved forest	12	10	7	15	0	0	27	0	18	0
Mixed forest	2	1	0	0	0	0	3	0	3	0
Undefined forest	3	3	4	3	0	0	7	0	1	0
Open fresh vegetation	9	7	15	22	0	0	17	0	7	0
Open medium fresh vegetation	11	10	30	30	0	0	1	0	5	0
Open sparse vegetation	10	10	27	19	0	0	0	0	0	0
Mire with forest	0	0	0	0	0	0	1	0	1	0
Open marsh	2	2	1	1	0	0	4	0	11	0
Barren mountains and rocks	5	2	7	4	0	0	0	0	0	0
Built and transport	2	1	0	0	0	0	2	0	4	0
Freshwater	4	4	6	5	0	0	3	100	3	0
Ocean	29	39	0	0	100	100	0	0	0	100

Table S2. Workshop attendance by municipality for PPGIS survey in 2020

Municipality	Date	No. Attendees
Osterøy	10/02	1
Modalen	11/07	4
Vaksdal	13/02	2
Radøy	17/02	2
Lindås	18/02	3
Meland	19/02	2
Fedje	24/02	8
Øygarden	25/02	2
Austrheim	26/02	0
Vaksdal	02/03	0
Gulen	05/03	0
Lindås	09/03	4
Radøy	10/03	0
Meland	11/03	2
Masfjorden	12/03	Cancelled due to COVID-19
Øygarden	16/03	Cancelled due to COVID-19
Osterøy	17/03	Cancelled due to COVID-19
Bergen	19/03	Cancelled due to COVID-19
Total		**30**

Table S3. Data sources used in MaxEnt modelling

Data	Description	Available from
LULC richness	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Agricultural land	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Forest	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Open land	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Water (including freshwater and ocean)	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Hiking trails	Open street maps	https://www.openstreetmap.org/
Roads	N50 data layer	https://www.geonorge.no/
Buildings	N50 data layer	https://www.geonorge.no/
Elevation	Digital elevation model (DEM) at 10 m resolution	https://www.geonorge.no/
Slope	Calculated from the DEM at 10 m using the 'slope' function in the *raster* package in *R*	https://www.geonorge.no/

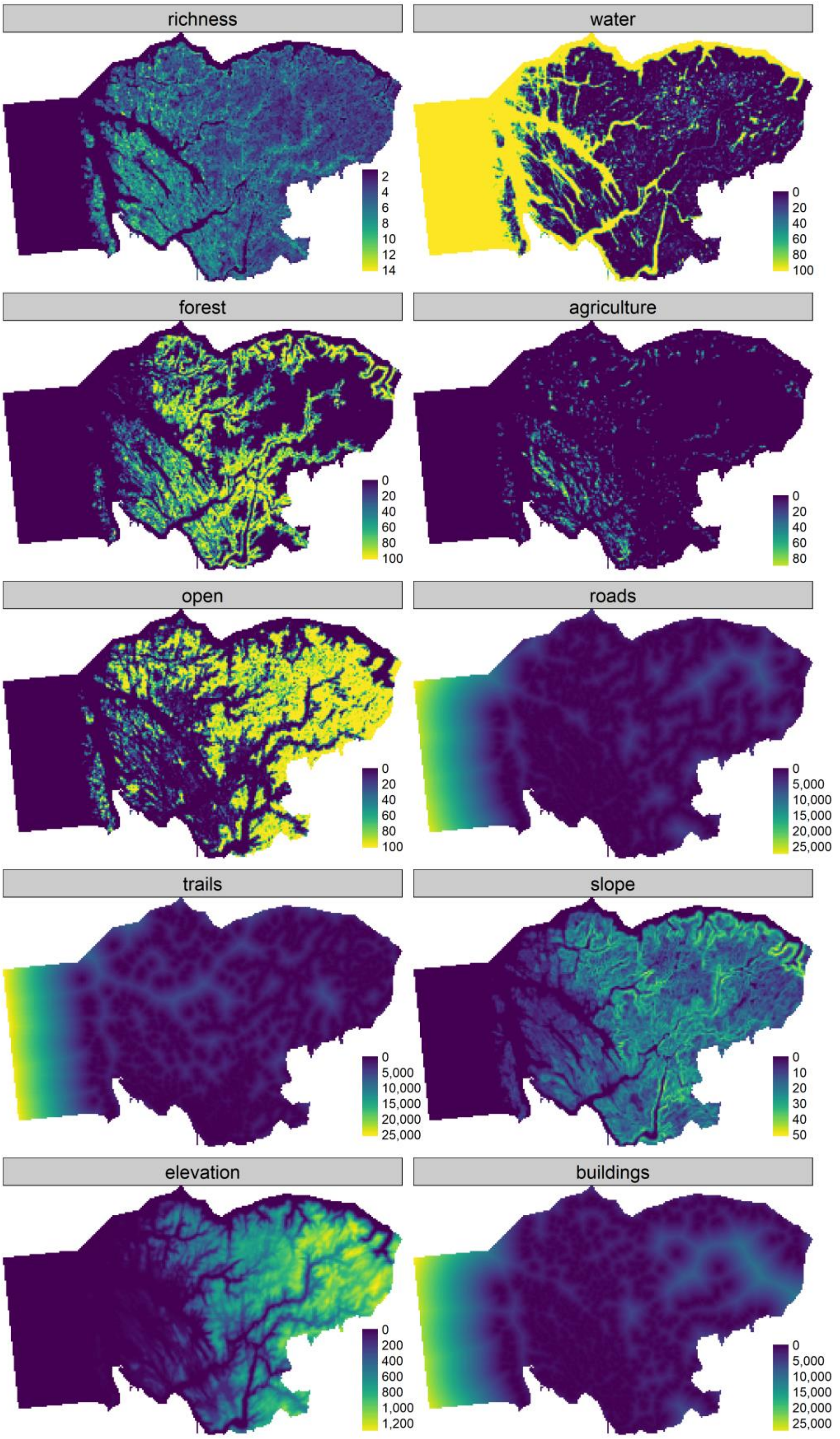

Figure S1. Spatial distribution of the 10 landscape characteristics at 500 m resolution used in the MaxEnt modelling.

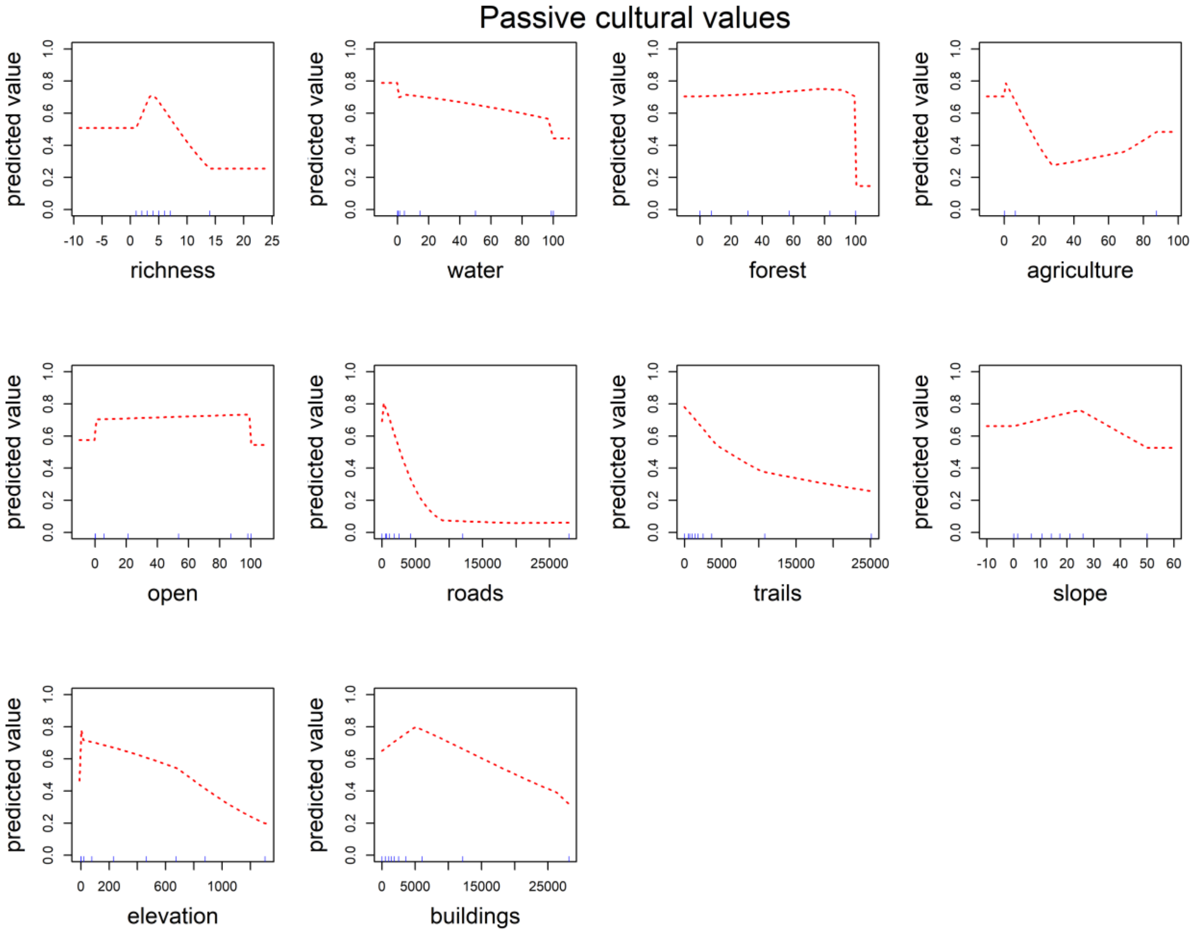

Figure S2. Response curves of the 10 variables included in the MaxEnt model for the passive cultural values bundle.

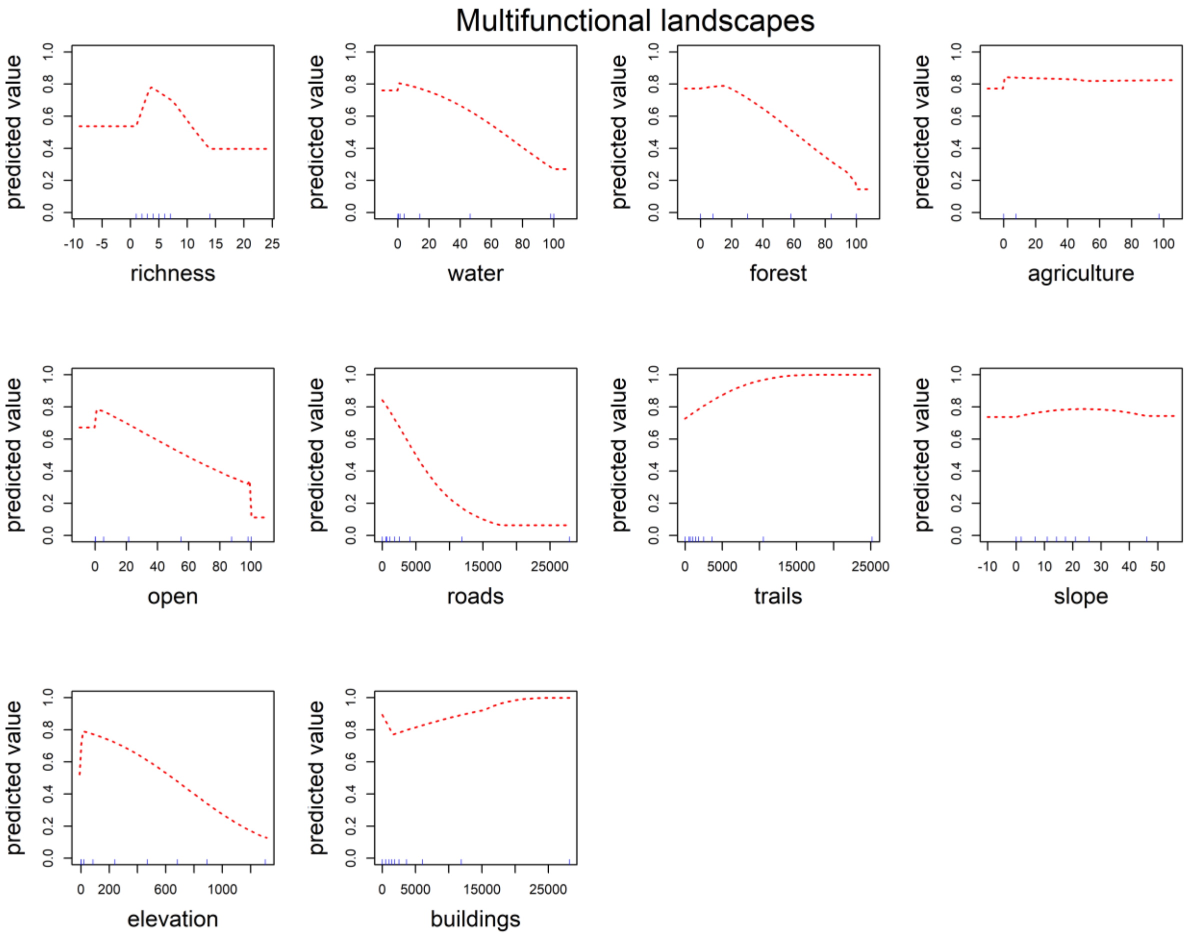

Figure S3. Response curves of the 10 variables included in the MaxEnt model for the multifunctional landscapes bundle.

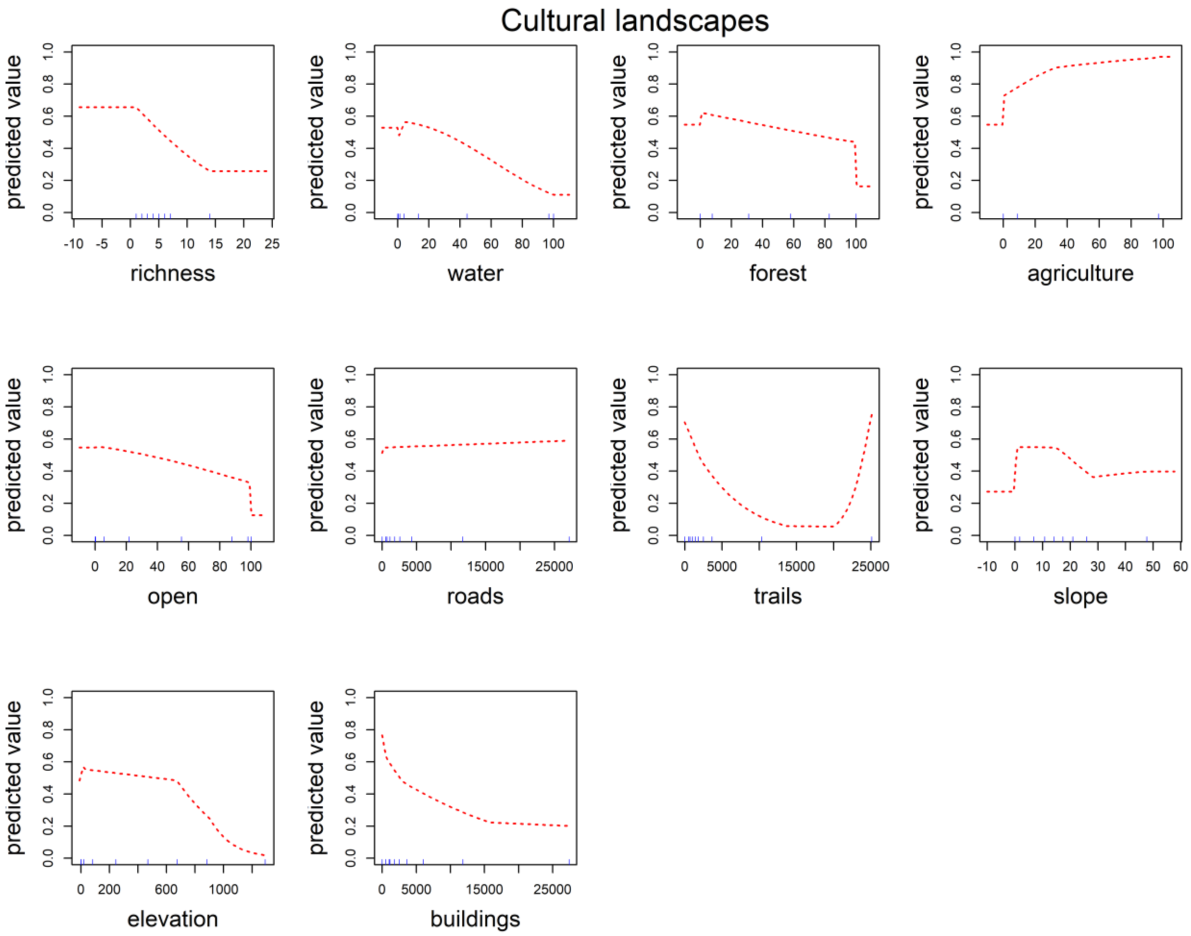

Figure S4. Response curves of the 10 variables included in the MaxEnt model for the cultural landscapes bundle.

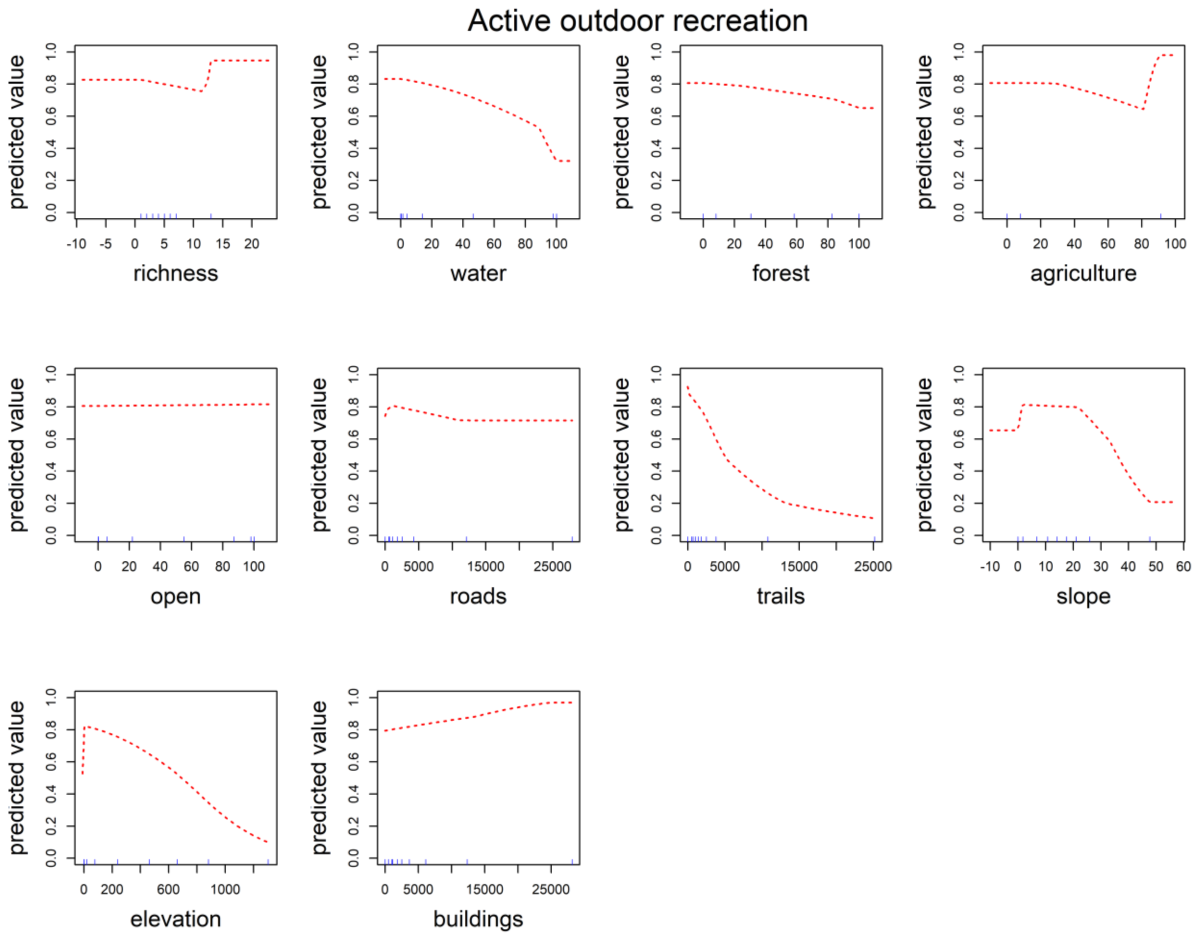

Figure S5. Response curves of the 10 variables included in the MaxEnt model for the active outdoor recreation bundle.

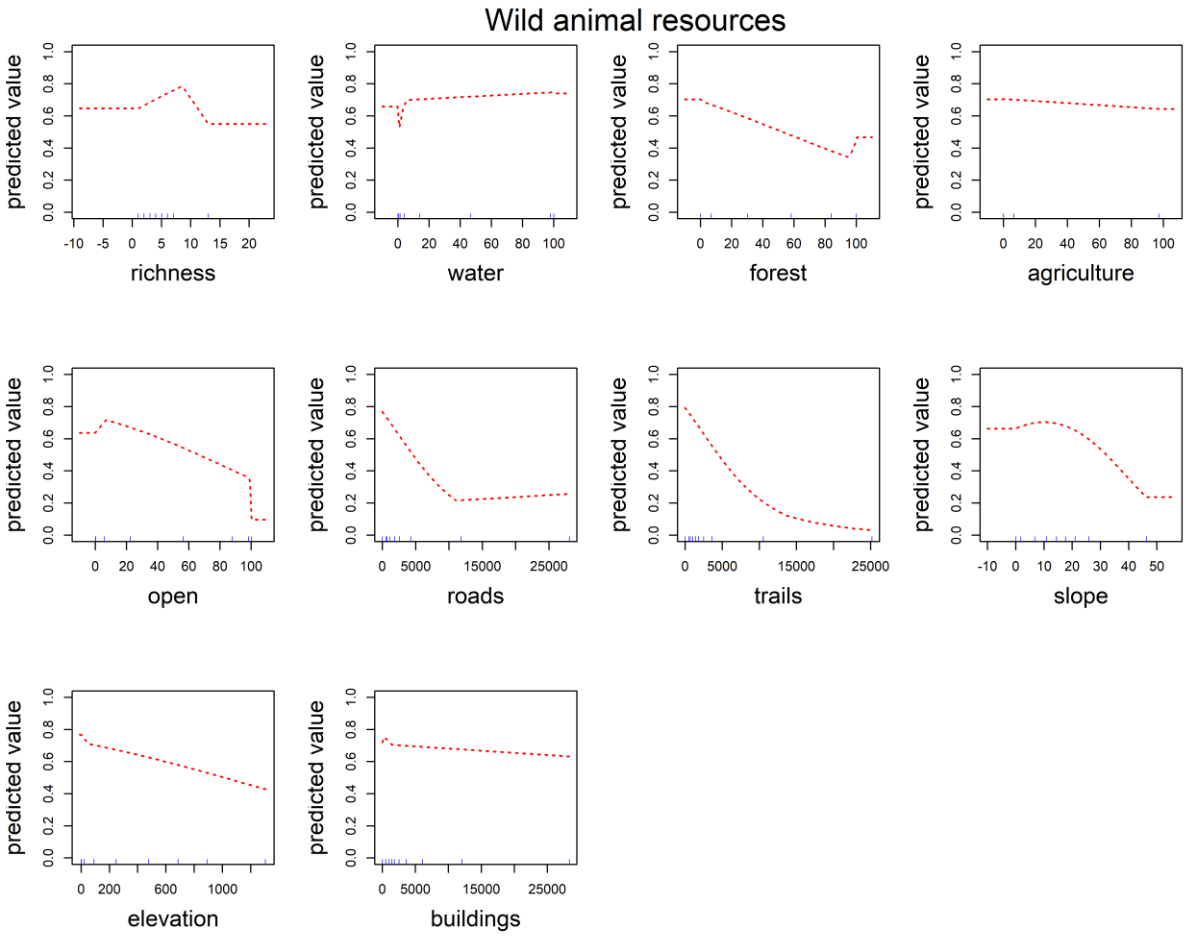

Figure S6. Response curves of the 10 variables included in the MaxEnt model for the wild animal resources bundle.

PAPER II

Integration matters: Combining socio-cultural and biophysical methods for mapping ecosystem service bundles

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The multifunctional cultural landscape of the strandflat in Alver municipality, Nordhordland Biosphere Reserve. The image depicts fjords, outfield grazing in coastal heathland, infield cultivated hayfields and patches of woodland and forest. This landscape is representative of Bundle 1 in Paper II. Photo: Peter Emil Kaland.

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RESEARCH ARTICLE

Integration matters: Combining socio-cultural and biophysical methods for mapping ecosystem service bundles

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Abstract Ecosystem services (ESs) play an important role in sustainable landscape management. People value ESs in diverse ways encompassing social and ecological domains and we need to bring these different values together. We used social-cultural and biophysical methods to map a diverse set of ESs at two spatial scales in a UNESCO Biosphere Reserve in Norway. The ESs bundled into three distinct social–ecological system archetypes which were similar in their distribution and relative ES values at both spatial scales. The bundles were also well matched to relative ESs values of the Biosphere Reserve zones (core, buffer, and transition) indicating that the bundles capture the social–ecological systems of the zones. We argue that it is important to consider the social–ecological context of the zones to provide sufficient knowledge to inform management. Our work has the capacity to contribute to sustainable land management that takes biocultural values into consideration.

Keywords Biocultural diversity · Biosphere Reserve zonation · Ecosystem service bundles · Socio-cultural values · UNESCO Biosphere Reserves

INTRODUCTION

Humans are intricately linked with, and are entirely reliant on nature and the ecosystem services (ES) that we co-produce with nature including clean water, fresh air and food, and intangible benefits like mental well-being (e.g. Millennium Ecosystem Assessment 2005; Bratman et al. 2012). This reliance is clearly reflected in the widespread mark we have left on the planet, with 69–76% of Earth's surface showing evidence of human modification, much of which is the result of our co-production of ES with nature (Ellis and Ramankutty 2008). The ES concept is now mainstream in social–ecological research and increasingly used in policies and land-use planning decisions from local to continental scales (Maes et al. 2012; Schröter et al. 2016; Schubert et al. 2018; Longato et al. 2021). In the last decade there have been significant conceptual shifts in ES thinking driven in part by the work of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and others (e.g. Mace 2014; Martín-López et al. 2014; Díaz et al. 2015; IPBES 2019). These shifts bring about a wholistic view of ES by acknowledging the plurality of contributions that nature makes to our wellbeing and recognising that our values for nature are not only instrumental, but are also intrinsic and relational (Díaz et al. 2015; Pascual et al. 2017; Kenter 2018; Maes et al. 2018; Kadykalo et al. 2019). Indeed, Nature's Contributions to People (NCP) is a term introduced by IPBES to capture those multiple values of nature from a broader range of society (Díaz et al. 2015, 2018). Although there has been substantial debate about how ES and NCP differ, it is overall reasonable to acknowledge that they are broadly similar, particularly in recent ES research (see Kadykalo et al. 2019). We therefore use the term ES throughout but recognise that some differences between the terms exist.

Multiple values of landscapes

Landscapes develop through interactions between nature and people through cultural, social, and economic practices (Olwig 2007). Focussing on either biophysical or social–

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cultural values in sustainability problems will fail to capture the full breadth of values offered by landscapes (Meyfroidt et al. 2022). Integrating different value types and ways of measuring (e.g. biophysical and socio-cultural) into ES assessments is an important step to implementing contemporary ES thinking into governance, management, and planning. Assessment and mapping of ES studies have often been constrained to either biophysical or economic approaches, although there are an increasing number of studies using socio-cultural and pluralistic methods (Martín-López et al. 2019; Schutter and Hicks 2021). Biophysical approaches have contributed substantially to the understanding of the spatial distributions and interactions between ES, particularly provisioning, and regulating and maintenance ES (Chan and Satterfield 2020). These biophysical methods link biological and physical attributes of the landscape to ES supply with varying degrees of complexity from simple proxy-based approaches assigning ES values to land use–land cover (LULC) types, to more complex process-based models that incorporate a diversity of parameters such as geochemistry, climate and biotic characteristics like plant traits (reviewed by Lavorel et al. 2017). However, biophysical methods have been somewhat limited in their capacity to map cultural ES and are lacking in their ability to capture social–cultural values of ES (Brown and Fagerholm 2015; Chan and Satterfield 2020).

We adopt the definition of socio-cultural values formulated by Scholte et al. (2015, p. 68) as “the importance people, as individuals or as a group, assign to (bundles of) ESs”. Methods that elicit the values that people assign to ES are therefore considered socio-cultural in our interpretation. Amongst studies using socio-cultural methods for ES mapping, Public Participation GIS (PPGIS) has become prominent in the literature (e.g. Plieninger et al. 2013; Brown and Fagerholm 2015; Fagerholm et al. 2019). The potential of PPGIS has been highlighted to address deficits in other mapping methods for cultural ES (Crossman et al. 2013; Brown and Fagerholm 2015) and several studies have combined PPGIS for cultural ES with other methods for provisioning and/or regulating and maintenance ES (Bagstad et al. 2017; Lin et al. 2017; Rolo et al. 2021; Zhao et al. 2021). These studies provide a basis for progressing research into relationships between multiple ES across all ES categories within landscapes for planning and management applications.

Ecosystem service bundles

Landscapes provide different ES, or sets of ES, depending on their configuration such as the areal extent of the ecosystems, the geological landforms, and type and intensity of human intervention within them (Bennett et al. 2009). ES bundles—“sets of ecosystem services that repeatedly appear together across space or time” (Raudsepp-Hearne et al. 2010, p. 5242) are widely used to assess the multifunctionality of landscapes and/or ecosystems (e.g. Raudsepp-Hearne et al. 2010; Turner et al. 2014; Queiroz et al. 2015), although it has been pointed out that bundles are not synonymous with multifunctionality (Saidi and Spray 2018). In a review Meacham et al. (2022) identified five benefits of using ES bundle analyses related to (1) simplifying analysis, (2) simplifying management, (3) developing practical social–ecological theory, (4) filling data gaps, and (5) acting as a bridging tool. In addition, ES bundles can assist in identifying social–ecological system archetypes within a landscape (Hamann et al. 2015). Since ES are co-produced by people and nature (Spangenberg et al. 2014), ES bundles can be recognised as distinct social–ecological systems that have emerged though complex interactions and feedbacks between social and ecological systems (Folke et al. 2010; Reyers et al. 2013; Hamann et al. 2015). These social–ecological system archetypes can provide important information to guide conservation planning and management, particularly in light of modern framing of conservation as ‘People and Nature’ (cf. Mace 2014).

Ecosystem services across scales

From a planning and management perspective it makes sense to map ES values and subsequent ES bundles at the spatial scale at which management decisions are made, and many studies have taken this approach and mapped ES bundles at the municipality scale (e.g. Raudsepp-Hearne et al. 2010; Queiroz et al. 2015; Malmborg et al. 2021). However, although governance decisions are often made at larger scales many ES are effectively produced and managed at much smaller scales such as the farm or field level. Therefore, mapping ES at a single scale may lead to a spatial mismatch between the scale at which ES are mapped and bundled, and the scale at which they are produced, managed, and/or governed (Raudsepp-Hearne and Peterson 2016). This scale-mismatch means that management actions to enhance a particular ES at one scale can result in trade-offs with other ES at different scales (Raudsepp-Hearne and Peterson 2016). Mapping and identifying ES bundles at multiple scales to account for the different scales that ES are produced, managed, and/or governed can contribute to addressing issues that may arise with such mismatches (Scholes et al. 2013).

Ecosystem services in UNESCO Biosphere Reserves

The United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserves (BRs) provide succinct case studies for exploring ES assessment,

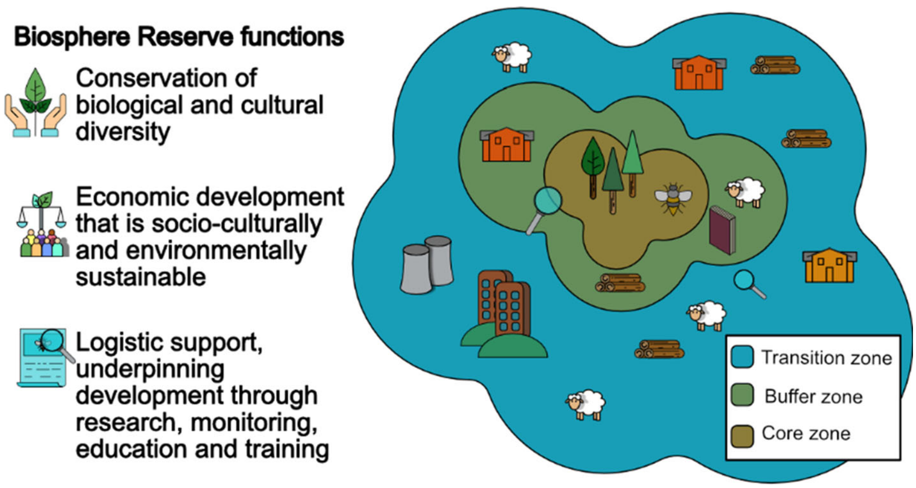

Fig. 1 Conceptual representation of the UNESCO Biosphere Reserve zonation and the three functions of Biosphere Reserves. Adapted from https://en.unesco.org/biosphere/

governance, and management in social–ecological landscapes. Biosphere Reserves are explicitly recognised as both sources and stewards of ES (UNESCO 2017) emphasised by recent requirements to report on the state of ES in periodic reviews. ES assessments can therefore be an important tool for monitoring success of BR objectives (Vasseur and Siron 2019; Palliwoda et al. 2021). Secondly, BRs are divided into three distinct zones; core, buffer, and transition/development (Fig. 1). Zonation provides the basis for achieving the three primary BR functions of (i) biocultural diversity conservation, (ii) sustainable development, and (iii) logistic support for research, monitoring, education and training (Fig. 1), and thus we can expect that zones provide different ES (Palliwoda et al. 2021). We use biocultural diversity as defined by Maffi (2005, p. 602) as the "diversity of life in all its manifestations—biological, cultural, and linguistic—which are interrelated within a complex socio-ecological adaptive system".

Several studies have mapped the spatial distribution of ES values in BRs using both biophysical methods (e.g. Kermagoret and Dupras 2018; Poikolainen et al. 2019) and socio-cultural methods (e.g. Plieninger et al. 2013; Cusens et al. 2022). However, few studies have the BR zonation explicitly in their analyses (but see Castillo-Eguskitza et al. 2019; Palliwoda et al. 2021; Cusens et al. 2022). Palliwoda et al. (2021) explicitly mapped and analysed the differences in ES co-production across the zones of 137 European BRs finding that ES co-production does not always match with the objectives of zonation within BRs. Castillo-Eguskitza et al. (2019) mapped biophysical and monetary ES values in Urdaibai BR, Spain, and assessed the coincidence between the two value types within the BR zones. Although these two studies highlight the value of zone-specific ES valuation for assessing BR goals and objectives, both consider zones as an aggregate of each zone type (i.e. core, buffer, and transition) within a BR. However, many BRs do not comprise a single core or buffer zone which means that aggregate ES values across all core or buffer zones may fail to capture the idiosyncrasies in ES values across each zone type. A recent study used PPGIS to map social-cultural values of the zones in Nordhordland Biosphere Reserve in Norway and found that values within zone types were quite variable pointing to the need for multiscale assessment of ES in BR zones (Cusens et al. 2022).

In our case study we combine biophysical and social-cultural methods to map 14 ES within Nordhordland Biosphere Reserve (NBR), a recently designated BR in Norway (Kaland et al. 2018). We first ask how ES provision varies across the BR zones in NBR. Second, we ask if there are distinct ES bundles within NBR, and if the spatial scale of bundles (municipal and grid) influences the relative ES values and spatial distribution of the bundles. Third, we ask how the ES bundles are captured within the BR zones in relation to their distribution and relative ES values. Finally, we discuss the potential applicability of ES bundles that integrate biophysical and socio-cultural methods to inform planning and management of biocultural diversity conservation in BRs, and other social–ecological systems more broadly.

MATERIALS AND METHODS

Study area

Nordhordland UNESCO Biosphere Reserve (hereafter NBR) is located on the west coast of Norway covering c. 6700 km^2 stretching from the open Atlantic Ocean in the west, through the low-lying coastal flats on the west coast, up to the mountains in the east (Fig. 2a). The terrestrial landcover comprises predominantly 'open and sparse vegetation' (34%) and forest (24%; Fig. 2b) with agricultural land making up 3%. Marine environments are cover a large spatial extent (29%) including open ocean and extensive fjord systems. The region is characterised by a mild wet-temperate oceanic climate with high mean annual rainfall (2400 mm/year). There is a strong west–east precipitation gradient from coast to the mountains with the coastal areas receiving 1300 mm/year whilst the upland areas receive 3000 mm/year. Mean temperature of the warmest and coldest months is 13.0–14.5 °C and 3.0–3.0 °C, respectively in the coastal areas. The administrative units comprise nine municipalities that are contained entirely with the boundaries of NBR, as well as a further five that are partially within the boundaries (Fig. 2a). The permanent human population of the nine main municipalities is c. 54 000 concentrated in low-lying southwestern coastal areas in the settlements of Knarvik, Frekhaug, Valestrandfossen, Lindås, and Manger (Fig. 2a).

The zonation of NBR comprises four localities with a core and buffer zone associated with each (Fig. 2b; Kaland et al. 2018). The zones represent the major land- and seascapes in NBR including the coast and outer archipelago (Lurefjorden), the marine and terrestrial components on the outer fjords (Osterfjorden and Loneelvi River), and the inland mountain landscape (Stølsheimen; Fig. 2b).

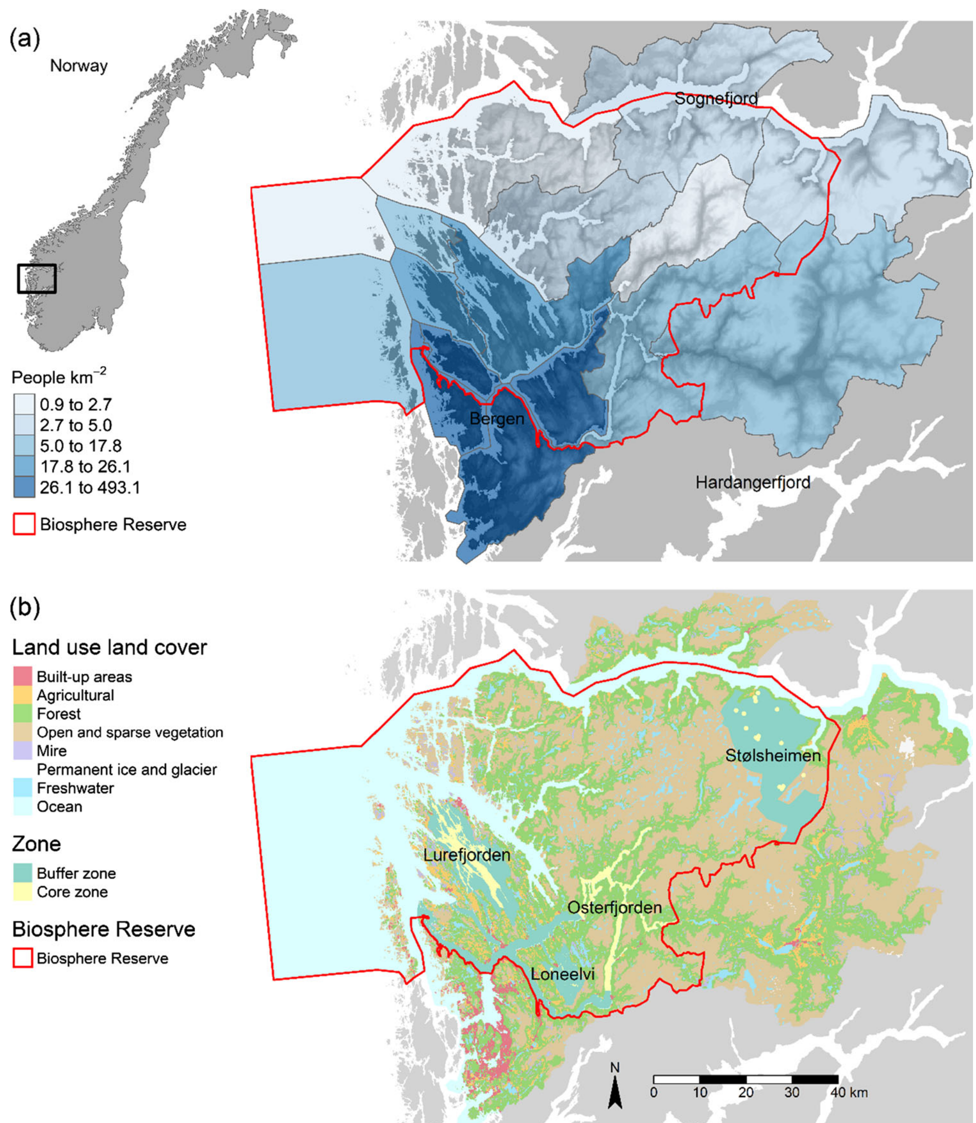

Fig. 2 **a** Location and population densities of the municipalities, and **b** land use–land cover and the location of the different zones in Nordhordland UNESCO Biosphere Reserve at the west coast of Norway

Each zonation locality has its own unique characteristics encompassing various components of the biocultural diversity found in NBR including cultural heritage monuments and upland summer farms at Stølsheimen, cultural landscapes in the buffer zones of Loneelvi and Lurefjorden, and important biodiversity and research sites in the core areas of Lurefjorden and the National Salmon Fjord in Osterfjorden.

Ecosystem services typology

The ES typology was developed in three steps. First, we used the NBR UNESCO application document (Kaland et al. 2018) to identify locally relevant ES. Second, we referred to published literature on ES mapping to find ES not previously identified. Finally, we used a workshop with local stakeholders to test the typology and identify any ES we had missed. We attempted to link our typology to the Common International Classification of Ecosystem Services version 5.1 (CICES; Haines-Young and Potschin 2018) and IPBES NCPs (Díaz et al. 2018) wherever possible. However, there are some cultural ES in our typology not strictly linked to single classes within CICES (e.g. inspiration, spiritual, and aesthetic) because the statements we used in PPGIS survey (see below) needed to be locally relevant and understandable to non-experts (Cusens et al. 2022). In addition, water yield has no equivalent within IPBES NCPs. The final typology contained 14 ES comprising five regulating and maintenance, four provisioning, and six cultural ES (Table 1).

Cultural ecosystem services

We used a web based PPGIS to collect socio-cultural values for ES in NBR in which participants mapped points related six cultural ES based on statements adapted from published PPGIS-ES studies (e.g. Fagerholm et al. 2016; Plieninger et al. 2019) capturing both use and subjective perceptions of socio-cultural values of ES (Scholte et al. 2015). For more information regarding the PPGIS survey please see Cusens et al. (2022). To model the distributions of cultural ES we use an approach similar to Sherrouse et al. (2014) using maximum entropy (MaxEnt) modelling with 10 spatially explicit social–ecological landscape characteristics at a 250 m resolution (distance from roads, buildings, and hiking trails, percentage cover of agricultural land, water, forest and open LULC types, and elevation, slope, and richness of LULC). The variables were identified from previous studies as well as additional variables considered important in NBR (Table S1; Sherrouse et al. 2014; Bagstad et al. 2017; Muñoz et al. 2020). For more detail on the modelling methods please refer to Appendix S1.

Regulating and maintenance, and provisioning ecosystem services

We used several approaches to map regulating and maintenance, and provisioning ES including: (1) national statistics available at the municipality and/or regional level downscaled to a grid (e.g. fodder production); (2) LULC proxy-based models (e.g. carbon storage); and (3) process-based models (e.g. water regulation) (Table 1). Values of each ES were normalised to unitless values between zero and one to enable comparison amongst different ES. See Appendix S1 for more detail on methods for each ES and data sources used.

Ecosystem services and Biosphere Reserve zonation

Similarly to Palliwoda et al. (2021), we assessed the levels of provision of ES in the BR zones by calculating the median values for each ES in each zone. Before extracting these values, we excluded all non-service providing areas for services provided by single ecosystem types (Table 1). For example, non-forested or cultivated land for timber and avalanche protection, and fodder, respectively. We plotted the relative ES median values amongst the three main zones and for each individual zone. To test for differences in ES supply we used pairwise Wilcoxon rank sum tests to test for differences of ES provision within each zone for the three main zones (i.e. core, buffer, transition) as well as only zones within the terrestrial or the marine environment. We made the pairwise comparisons between core vs. buffer, buffer vs. transition and core vs. transition for each ES.

Ecosystem service bundles

We produced ES bundles at two spatial scales (1) using municipalities (mean = 422.6 km^2) and (2) 250 × 250 m grid cells as the spatial units. For the municipality scale we aggregated the grid scale data and calculated the mean value for each ES per municipality. We excluded the municipalities with less than 30% of their area within NBR resulting in 10 entire and three partial municipalities for the bundle analysis. For the grid scale we used the values per grid cell. Bundles were produced following a similar methodology of many other studies (e.g. Raudsepp-Hearne et al. 2010; Saidi & Spray 2018; Quintas-Soriano et al. 2019; Malmborg et al. 2021). At both scales we first reduced the dimensionality of the dataset with principal component analysis and selected the number of components that explained at least 65% of the variance and applied varimax rotation. Finally, we used *k*-means clustering to assign either municipalities or grid cells to clusters. We then chose the best number of clusters using the 'Elbow method' on the varimax rotated factor loadings.

Table 1 An overview over the 14 ecosystems services (ES), the service providing areas (SPAs), and the methods used for mapping them

ES	SPAs	Method/index	Units	References
Cultural				
Appreciation of biodiversity	All areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Cultural heritage	All areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Hunting and fishing[a]	All areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Inspiration, spiritual and aesthetic	All areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Outdoor recreation	All areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Wild plant, berries and mushrooms[a]	All terrestrial areas	PPGIS and MaxEnt modelling	Unitless (0–1)	Sherrouse et al. (2011)
Regulating and maintenance				
Avalanche protection	Forested areas	Avalanche Protection Index	Unitless (0–1)	Cordonnier, et al. (2014)
Global climate regulation	All areas	Sum of carbon stored in vegetation and soil	ton/ha	For example, Mitchell et al. (2021)
Habitat quality	All areas	Phenomenological model of LULC, landscape metrics and threats	Unitless (0–1)	For example, Ruas et al. (2021)
Soil retention capacity	Vegetated terrestrial areas	Revised Universal Soil Loss Equation	ton/ha/year	Quintas-Soriano et al. (2019) and Renard et al. (1991)
Water retention	All terrestrial areas	Water Retention Index	Unitless (1–10)	Vandecasteele et al. (2018)
Provisioning				
Animal fodder	All terrestrial areas	Statistical downscaling based on land cover	ton/ha/year	Crouzat et al. (2015) and Statistics Norway (2019)
Drinking water	Cultivated areas	InVEST water yield model	mm/ha/year	Sharp et al. (2020)
Timber and firewood	Forested areas	Species and site quality specific annual timber increment	m3/ha/year	Schröter et al. (2014)

[a]These two ES are classified as provisioning ES by CICES. However, we have classified them as cultural services, consistent with the socio-economic background of our study region (Reyes-García et al. 2015)

After we had assigned municipalities or grid cells to clusters, we calculated the mean value for each ES per cluster and represented these using flower-petal diagrams. In addition to generating the bundles, we calculated the percentage cover of LULC types within each bundle at both scales to qualitatively describe the social–ecological characteristics of the bundles. Land cover alone has previously been shown to be a strong predictor of ES bundle distribution (Meacham et al. 2016; Rolo et al. 2021). In addition, to compare how the bundles overlap with the different BR zones, we calculated the spatial overlap between the zones and the bundles and report this as a proportion.

Software

We used *R* (R Core Team 2021) for all data manipulation, analysis, and visualisation (Table 2).

RESULTS

Ecosystem service distributions

In general, cultural, and provisioning ES tended to have higher values in the lowland coastal municipalities and terrestrial areas to the west although, water yield was highest in the eastern highland areas (Fig. 3). Regulating and maintenance ES were more spatially variable with

Table 2 R packages (R Core Team 2021) used for data manipulation, analysis, and visualisation

Package	Analysis/task	References
EMNeval	Maximum entropy modelling	Kass et al. (2021) and Muscarella et al. (2014)
factoextra	Cluster analysis	Kassambara and Mundt (2020)
ggplot	Plotting	Wickham (2016)
ggpubr	Plotting and analysis	Kassambara (2020)
landscapemetrics	Landscape metrics calculation	Hesselbarth et al. (2019)
psych	Principal component analysis	Revelle (2021)
raster	Raster data	Hijmans (2020)
sf	Vector data	Pebesma (2018)
spatialEco	Kernel density calculation	Evans (2020)
stars	Raster data	Pebesma (2022)
tidyverse	General tidy workflow	Wickham et al. (2019)
tmap	Spatial plotting	Tennekes (2018)

water retention, avalanche protection, and sediment retention generally highest in the eastern upland areas, whereas habitat quality was highest in marine environments and climate change mitigation highest is the lowland terrestrial areas and municipalities. The grid scale mapping reveals some nuanced spatial variation not evident at the municipal scale including the very limited distributions of fodder production, avalanche protection, and sediment retention (Fig. 3b). Cultural heritage has highest values in the lowland areas within agricultural landscapes (Fig. 3b). In addition, the grid scale demonstrates the predominantly marine distribution of hunting and fishing indicating that this ES comprises predominantly fishing within NBR (Fig. 3b).

Ecosystem services and Biosphere Reserve zonation

Ecosystems service values were variable across the three main aggregate BR zones (i.e. core, buffer, transition; Fig. 4a). The distribution of ES values was similar in the buffer and transition zones whilst the core zone was quite distinct (Fig. 4a). Cultural ES tended to have higher values in the core zone and lowest values in the transition zones aside from wild plants, berries and mushrooms which was comparatively low in all zones. Provisioning ES values were lowest in the core zone and moderately higher in both buffer and transition zones. Habitat quality was consistently high in all three zones although highest in the core zone.

Amongst the individual zones paired core and buffer zones tended to have similar relative ES supply values (Fig. 4a and c). Specifically, the core and buffer zones within Loneelvi, Stølsheimen, and Osterfjorden core and buffer zones were similar. Further, there was a considerable contrast between terrestrial and marine zones overall (Fig. 4b and c). Provisioning and regulating and maintenance ES supply values were low in marine zones in comparison to the terrestrial zones. Marine zones were like each other although the marine transition zone had lower values for cultural ES than the marine core and buffer zones (Fig. 4c). Further, the ES supply values of aggregated core zones (Fig. 4a) were similar to the individual marine zones (Fig. 4c).

Ecosystem service bundles

We identified three ES bundles at both grid and municipal scales (Fig. 5). The spatial distribution of the bundles was similar with both scales consisting of a south-central located bundle (Bundle 1) in the higher populated areas and municipalities, a second (Bundle 2) to the west encompassing marine dominated areas and municipalities, and a third north-west located bundle (Bundle 3) in the more mountainous areas and municipalities (Fig. 5). The total area covered by the bundles differs at the two scales despite their similar spatial distributions (Table 3). The relative values of different ES of the bundles were very similar at both scales. Bundle 1 had high values for all cultural ES and moderate values for provisioning and, regulating and maintenance ES. Bundle 2 had high values for habitat quality and hunting and fishing. Bundle 3 had high values for water supply and moderate values for water retention and habitat quality (Fig. 5).

Comparing zones and bundles

The relative ES values in Bundle 1 was most like buffer zone of Lurefjorden, and both the core and buffer zones of

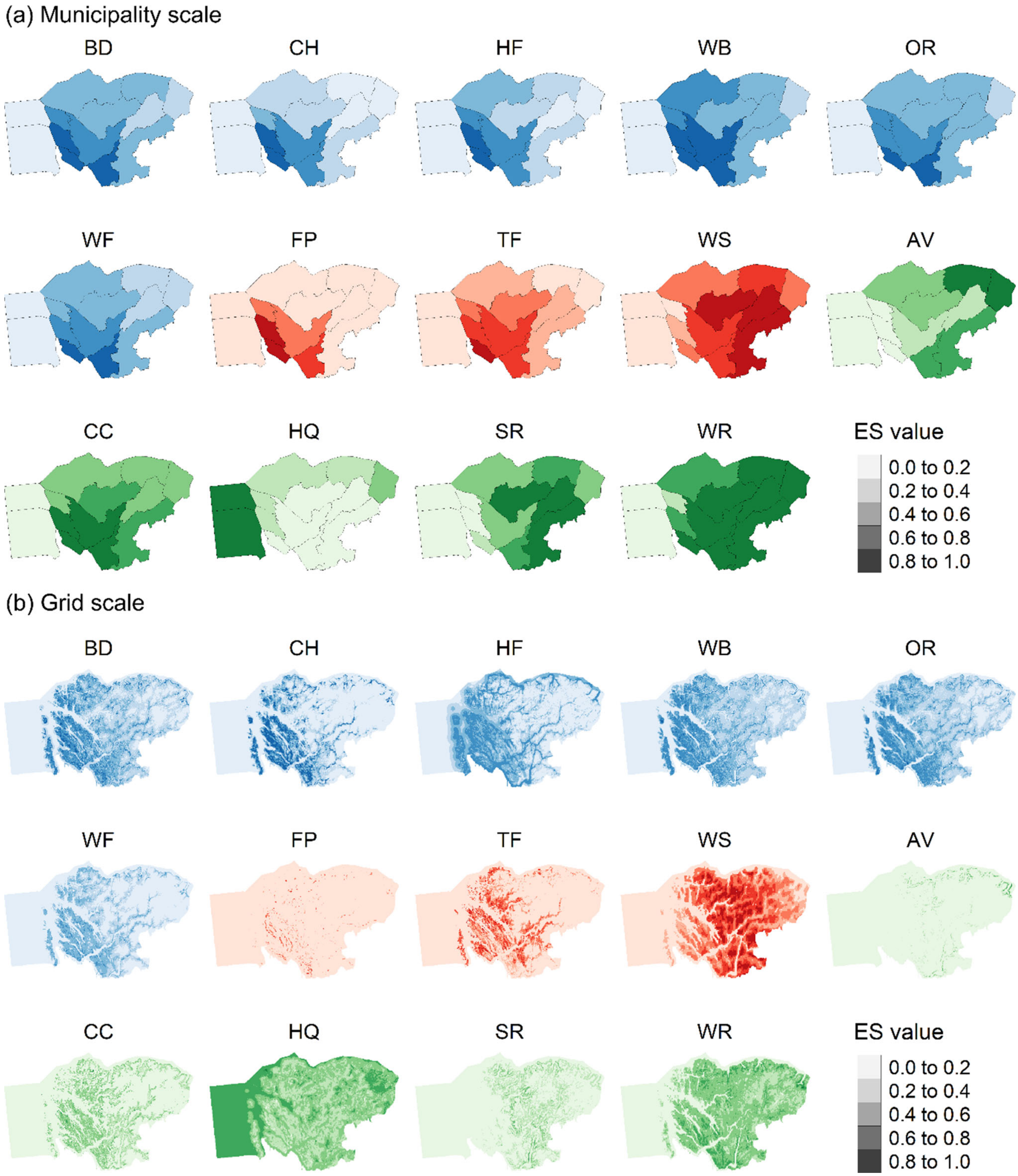

Fig. 3 Distribution of normalised ecosystem service (ES) values of 14 ES at the **a** municipality scale and **b** the grid (250 × 250 m) scale in Nordhordland Biosphere Reserve. Cultural ES in blue, provisioning ES in red and, maintenance and resulting ES in green. *BD* appreciation of biodiversity, *CH* cultural heritage, *HF* hunting and fishing, *WB* inspiration, spiritual, and aesthetic, *OR* outdoor recreation, *WF* wild plants, berries or mushrooms, *FP* fodder production, *TF* timber production, *WS* water yield, *AV* avalanche protection, *CC* climate change mitigation, *HQ* habitat quality, *SR* sediment retention, *WR* water retention

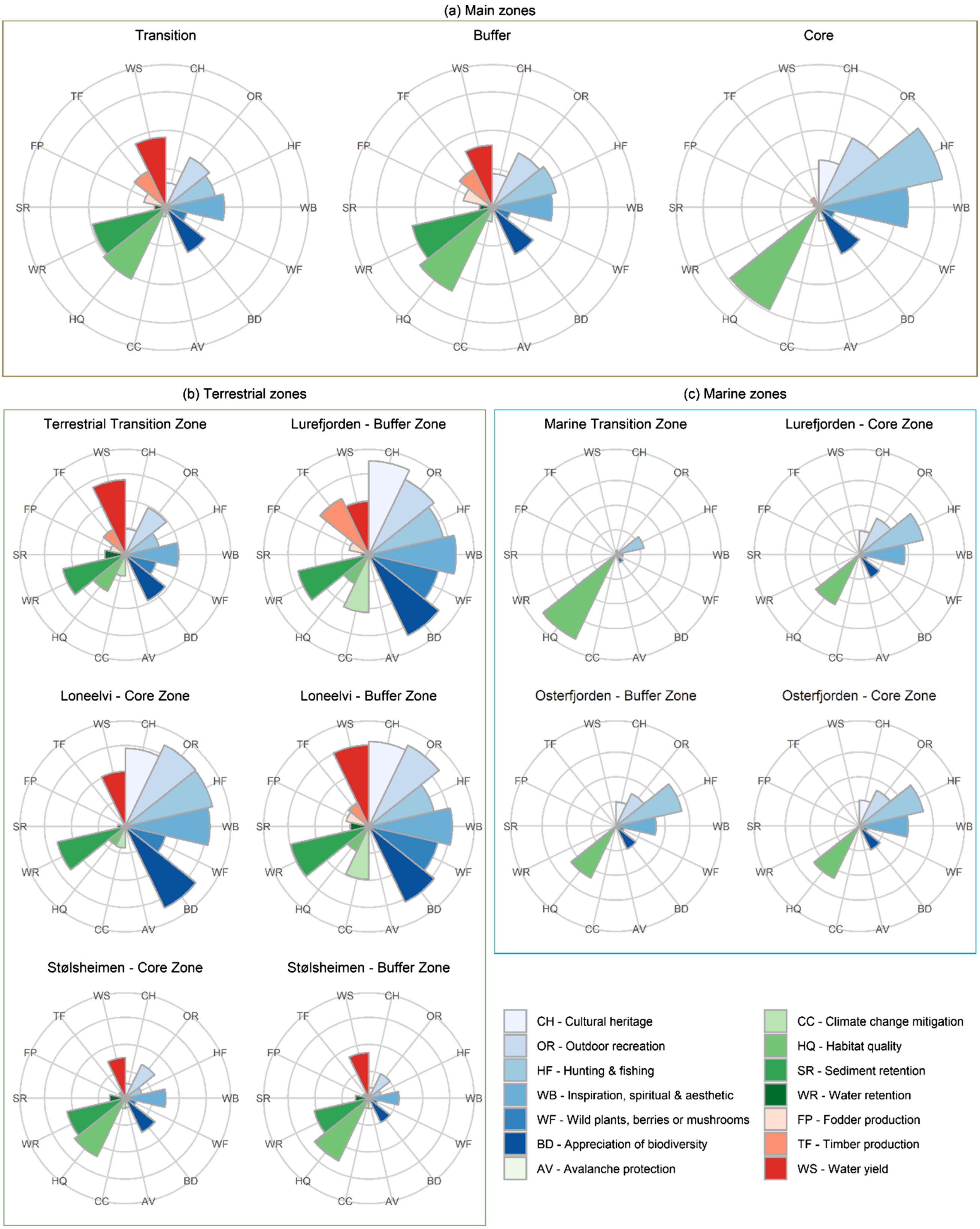

Fig. 4 Median values of 14 ecosystem services in the **a** three main biosphere reserve zones, and individual zones separated into **b** terrestrial (and one freshwater) and **c** marine areas

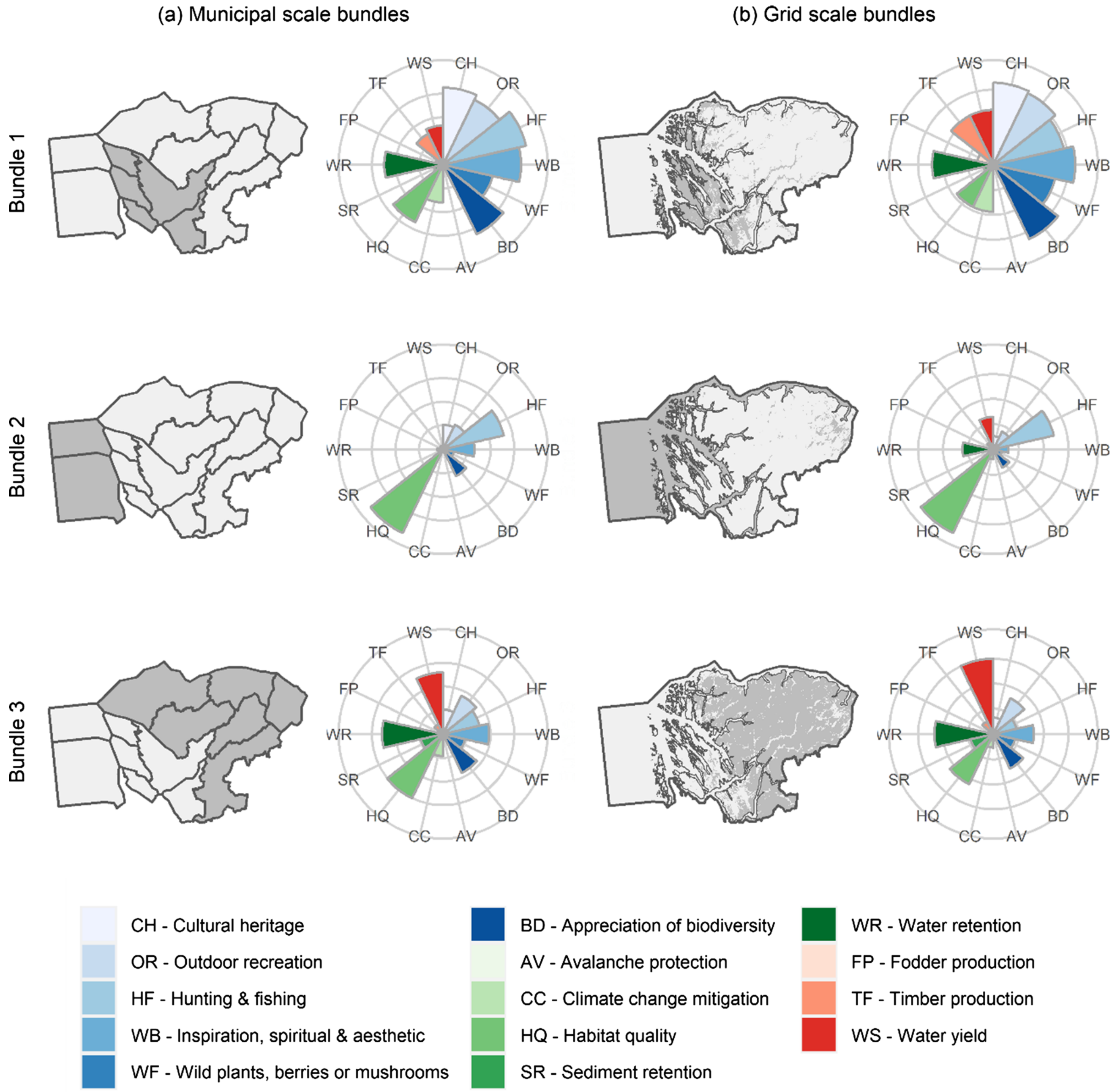

Fig. 5 Distributions and mean values of 14 ecosystem services in the three bundles identified at **a** municipality and **b** grid (250 × 250 m) scales in Nordhordland Biosphere Reserve

Loneelvi, Bundle 2 was most similar to the marine transition zone and to a lesser extent the core and buffer zones of the other marine dominated areas, and Bundle 3 was most similar to the terrestrial transition zone and to a lesser extent the core and buffer zones of Stølsheimen (Figs. 4, 5). An overlay of the areal extent of the bundles and the zones revealed that the lowland terrestrial and freshwater zones comprise entirely or almost entirely of Bundle 1 at the municipal and grid scales respectively (Fig. 6). Similarly, the terrestrial transition and upland core and buffer zones comprise predominantly Bundle 3 at both scales (Fig. 6). At the grid scale all marine zones comprise predominantly Bundle 2 (Fig. 6). In marine zones at the municipal scale, however, there is substantial variation in the bundle composition of the zones (Fig. 6). Lurefjorden core and Osterfjorden buffer comprise predominantly Bundle 2, whereas Osterfjorden core is predominantly within Bundle 3.

Table 3 The number of spatial units (municipalities or grid cells) and spatial area of the three ecosystems service bundles identified in Nordhordland UNESCO Biosphere Reserve

Bundle	No. spatial units	Area of bundle (km^2)	Percent of bundle (%)
Municipality scale			
1	5	1459.85	22.1
2	2	1462.20	22.1
3	6	3688.03	55.8
Grid scale			
1	22 225	1389.10	20.5
2	39 833	2489.60	36.8
3	46 132	2883.30	42.6

DISCUSSION

Integrated mapping matters

We combined socio-cultural and biophysical methods to map 14 ES in a UNESCO Biosphere Reserve. The mapped ES were then used to compare ES supply across zones and to assess bundles of ES within the BR. Integrating socio-cultural and biophysical methods revealed some important insights about the distribution of ES values amongst the zones and the bundles we identified. The socio-cultural method for mapping cultural ES adds an important dimension to the mapping, and many ES would be unrepresented, and the composition of ES bundles would be substantially different if only biophysical methods were used (Bagstad et al. 2016). This is emphasised in our finding of a predominance and high diversity cultural ES in zones and bundles in areas close to more human modified landscapes (see for example Bundle 1 vs. Bundle 3 in Fig. 3). Biophysical methods alone limit the number and types of cultural ES that could be assessed due to limited knowledge on their distributions in different contexts. However, if only socio-cultural methods were used, we would fail to capture the distribution and values of a diverse set of ES beyond cultural ES alone. Firstly, there would be limited information on regulating and maintenance ES, since values for this ES class are typically

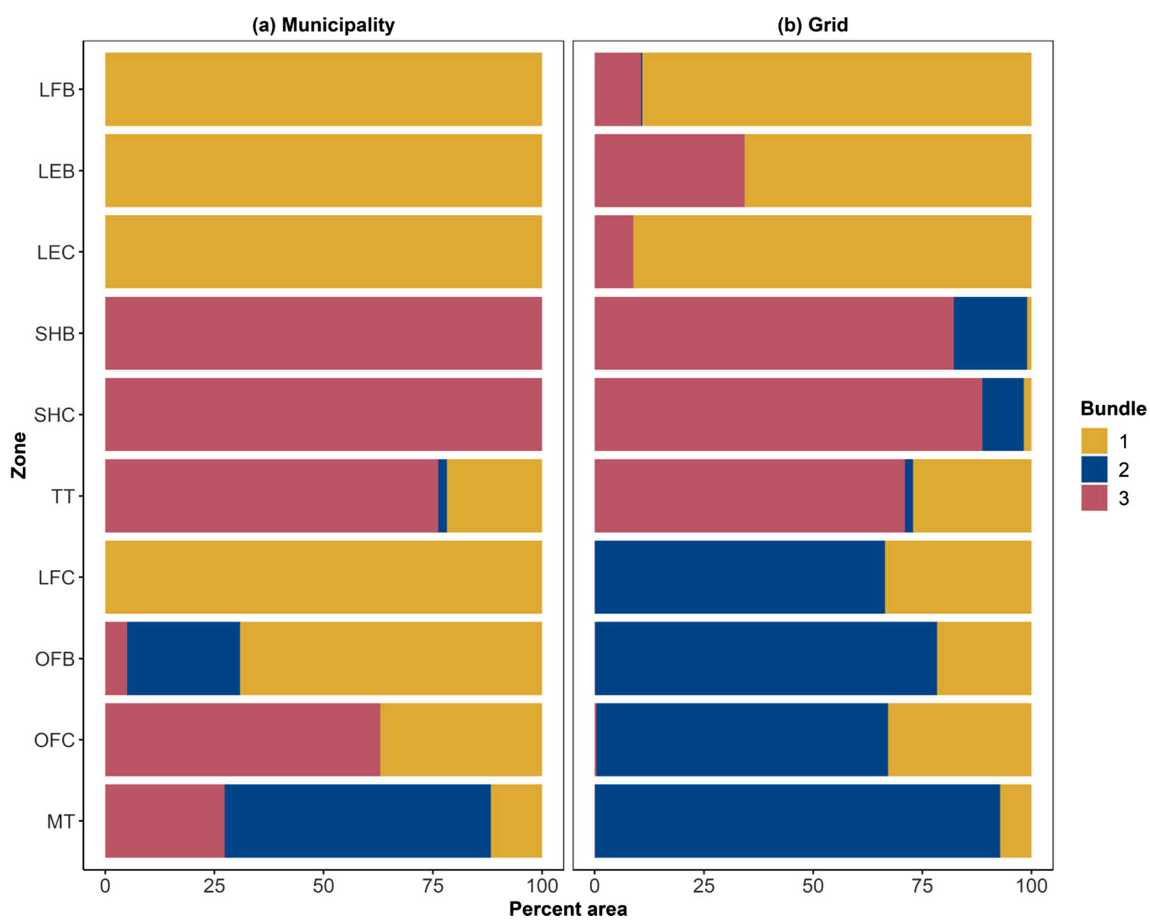

Fig. 6 Proportional bundle composition of each zone in Nordhordland UNESCO Biosphere Reserve at the **a** municipality and **b** grid scales. *MT* marine transition, *OFC* Osterfjorden core, *OFB* Osterfjorden buffer, *LFC* Lurefjorden core, *TT* terrestrial transition, *SHC* Stølsheimen core, *SHB* Stølsheimen buffer, *LEC* Loneelvi core, *LEB* Loneelvi buffer, *LFB* Lurefjorden buffer

mapped at low proportions relative to other ES in PPGIS studies, especially when compared to cultural ES (e.g. Garcia-Martin et al. 2017; Fagerholm et al. 2019; Cusens et al. 2022). Secondly, places further from human settlements would be underrepresented in our ES maps because low populated areas in the mountains had very few places mapped in our PPGIS study (41 or 3155 places) comprising almost entirely outdoor recreation (Cusens et al. 2022). This stems from both spatial discounting, where people map more places close to home (e.g. Brown and Kyttä, 2014; Fagerholm et al. 2019) and that people tend to not perceive complex processes involved in regulating and maintenance ES (Scholte et al. 2015). Our approach contributes to a growing literature and calls to bring together multiple approaches to ES assessment and mapping (e.g. Martín-López et al. 2019; Chan and Satterfield 2020). We show how mixed-methods can help highlight places with high cultural ES values as well as provisioning and maintenance and supporting ES values, providing a more holistic approach to ES mapping.

The spatial scale of the social–ecological system archetypes

Each of the three bundles we identified in NBR were distinct in their relative ES values. At the same time, bundles at different spatial scales were remarkably similar in both relative ES values and in their distribution. The consistency of the bundles across scales is the result of strong and clear social–ecological gradients characterised by both the land- and water-forms, land-use intensity, and the human populations and associated infrastructure. We interpret the bundles in our study as three distinct social–ecological systems archetypes comprising the low-lying ‘coastal flats’ with higher population density and mixed LULC types (Bundle 1), of predominantly marine and fjord dominated systems (Bundle 2), and the less populated mountainous regions in the east comprising predominantly open vegetation and to a lesser extent forest (Bundle 3) (see Appendix S3, Fig. S4 for proportions of LULC types in each bundle). In regard to scale, our results contrast with Raudsepp-Hearne and Peterson (2016) who found clearer differences in ES values between their smallest grid-scale (1 km^2) and larger municipality scales. The spatial extent in their study was significantly smaller than ours (c. 700 vs. c. 6700 km^2), and the landscape was dominated by agriculture, whereas our study site has a greater diversity of LULC types including significant marine areas and comparably low human populations with low land-use intensity. Large spatial extents are more likely to include more distinct landscape types than smaller spatial extents which in turn will influence ES, ES bundles and the social–ecological system archetypes contained within the landscape (Saidi and Spray 2018; Meacham et al. 2022). Our results indicate that scale has a small effect on ES bundle identification across large spatial scales with clear and strong social–ecological gradients, which is consistent with Madrigal-Martínez and Miralles I García (2020). Our bundles were intuitive in that they followed clear geographical gradients in the region and could be a useful communication tool for stakeholders and institutions (Malmborg et al. 2021). If ES typologies are locally contextualised through engagement with relevant stakeholders concerned with decision making and management as we have done, the ES bundles produced with that typology can be better grasped by those stakeholders (Malmborg et al. 2021). Despite the strong congruence in bundles at the grid and municipal scales, we do emphasise that the overlap is imperfect and identifying the mismatch between underlying social–ecological characteristics at the grid scale and administrative boundaries is important for operationalising our findings for management and planning (Crouzat et al. 2015).

Ecosystem services across zones

We found differences in relative ES provision between the aggregated transition and core zones, but this difference was not evident between transition and buffer zones. Cultural ES, recreational hunting and fishing in particular, were higher in the aggregated core zone whilst provisioning ES were higher in the transitions and buffer zones (Appendix S2, Fig. S1). Castillo-Eguskitza et al. (2019) also found higher levels of cultural ES supply in core zones than other zones, which in combination with low levels of provisioning ES is consistent with the objective of BRs for biocultural conservation. In contrast, Palliwoda et al. (2021) found that differences in ES supply between transition and buffer zones were more marked although we note that Palliwoda et al. (2021) excluded all marine zones from their analysis. Indeed, when we excluded marine areas from our analysis, we found more variation in the differences in ES supply across zones (Appendix S2, Fig. S2).

In both previous studies, only aggregated zones were considered, yet many BRs comprise multiple individual core and buffer zones, each of which may be dominated by one or few LULCs and the importance of disaggregated zonation assessment has been shown by Cusens et al. (2022), which focussed on the socio-cultural values of ES. Our consideration of multiple ES in individual zones rather than aggregated core and buffer zones identifies important nuances in relative ES supply amongst zones. We highlight that environmental context (social and ecological factors) has a strong influence on relative supply of multiple ES, which is swamped by aggregation, regardless of what type of zone is assessed. Thus, to capture the full breath of biocultural diversity within the BR zones it is crucial to consider zones individually. This argument is similarly identified in recent debates regarding the utility of 'global maps' for conservation priority setting (Wyborn and Evans 2021; Chaplin-Kramer et al. 2022).

Bundles to guide Biosphere Reserve planning

In our study each of the ES bundles contained all or part of at least one core and one buffer zone in addition to transition area, aside from the Bundle 2 at the municipality scale which did not contain any core area. Moreover, the relative ES values we found in our bundles share similarities to those of the ES values in the BR zones and the similarities were at least partially explained by the shared proportions of different LULC in the zones and related bundles (see Appendix S3 Figs. S4 and S5). Despite the relative simplicity of LULC as an indicator, LULC is an important determinant of ES supply and has been shown to be important in explaining the distribution of ES bundles (Meacham et al. 2016). We believe that ES bundles that identify SES archetypes have the potential to guide the planning of BR zonation. The focus on biocultural diversity conservation in BRs means that zonation should focus on the relationships between people and nature, which can be succinctly captured through ES bundles (Meacham et al. 2022). Since ES bundles can in effect capture SES archetypes (Hamann et al. 2015), selecting areas for core and buffer zonation that are representative of the different SES archetypes can contribute to conservation of biocultural diversity. Our assessment of the zonation in NBR fits relatively well with the SES archetypes identified in the bundle analysis with each SES archetype captured in at least one core and one buffer zone. This suggests that based on the different ES and methods we have used for mapping those ES, the zonation has the potential to provide conservation of the biocultural diversity within NBR. However, for this conservation to be realised, there is a need for integrated management across municipalities and scales. Our integrated approach of biophysical and social–cultural methods for assessing ES bundles aligns well with the biocultural diversity focus of BRs and we believe this provides better guidance for addressing the challenges of biocultural conservation goals.

Several authors have already highlighted the potential utility of UNESCO BR organisations to connect diverse stakeholders across spatial and administrative scales (e.g. Olsson et al. 2007; Schultz et al. 2018; Barraclough et al. 2021). This has important implications for ES management and governance due to the cross-scale nature of ES governance, production, management, and use. Management actions and production of ES are often realised at site and/or local scales, whereas regulations governing ES are more common at regional and national levels (Gómez-Baggethun et al. 2013; Raudsepp-Hearne and Peterson 2016). Our multi-scale assessment of ES bundles was important to test for variance of the emergent ES supply levels at different spatial scales at which they are produced, managed, and governed. By identifying that ES supply bundles are relatively stable and similar at grid and municipal scales suggests that actions that affect ES at small spatial scales may emerge and be detectable to a certain degree at larger scales. This can be particularly relevant in NBR because legislature governing land use, and planning and building in Norway are applied nationally but the administration of these acts is decentralised to municipalities (Landbruks- og matdepartementet 1995; Kommunal- og distriktsdepartementet 2008). Recent work on the social network in connection with various activities related to ES has shown that the BR organisation is well connected across many stakeholder groups in NBR, including regional and local government, farmers, hunters and fishers, and industry (Barraclough et al. 2022). This high level of connectivity of the BR organisation combined with our ES bundles has potential to contribute to ES governance within NBR. First, the high level of connectivity can assist in bringing stakeholders involved in natural resources together since BR organisations can act as a bridging institution. Second, the ES bundles can provide an interesting and engaging starting point for stakeholders to contribute to discussions and implementation of co-management of ES across different scales (Malmborg et al. 2021). Third, high connectivity can improve the flow of information between relevant stakeholders and contribute to adaptive governance approaches that is particularly well suited to SES governance and has been successfully implemented in BRs (Olsson et al. 2004, 2007). This is key since highly connected bridging organisations can be particularly effective in networks at identifying wider threats as well as the opportunities to address those threats (Olsson et al. 2007).

Reflection on our methods

We have considered the proportion of different LULCs within each bundle as a potential explanation for their distribution. Amongst the methods for modelling and mapping ES we have used, many are based on LULC, topographic and other social–ecological characteristics of the landscape (e.g. distance to infrastructure). Any attempts to statistically explain the distribution of the bundles would invariably have used the same variables, or variables derived from those used in the ES mapping. We believe there is a high risk of circularity in reasoning if we had used the same data for predicting the ES as we had used in mapping them (Spake et al. 2017; Saidi and Spray 2018).

Further, it is likely that we would increase the error by introducing additional uncertainty on top of the ES models (e.g. Puy et al. 2021). We therefore argue that the explanations with LULC captures a broad range of social–ecological characteristics in the landscape due to the way that strong environmental gradients have shaped the social–ecological landscape and associated land use over millennia.

We have combined an ES mapping and assessment exercise across marine and terrestrial systems. Amongst the ES indicators we have used, many are expressly terrestrial based. This is important to consider since marine resources make important contributions to the economic and cultural character of our study region. Our results should be interpreted with caution in relation to definitive policy or planning decisions related to ES management, particularly in the marine environment. However, we are confident that the patterns we found amongst zones, and the presence and distribution of the bundles would remain or be only marginally different if additional marine-specific ES—aquaculture and commercial fishing most prominently—were included, due the palpable differences in the types of ES supplied by marine and terrestrial systems. Our inclusion of the social-culturally based cultural ES provides an important component for the marine environment. For example, we found that recreational fishing is prominent in the coastal and fjord systems and largely absent from the open ocean in the marine transition zone.

CONCLUSION

We integrated biophysical and social-cultural methods for mapping and assessing ES in a multifunctional landscape unified by a UNESCO Biosphere Reserve (BR). The integrated mapping enabled us to undertake a comparative analysis across the zones of the BR and ES bundle assessment that accounted for biocultural diversity, consistent with the objectives of BRs. The analysis of relative ES values amongst zones showed the importance of considering the social–ecological context of the zones and not only their identity (i.e. core, buffer, or transition). We found that the ES bundles were informative in identifying SES archetypes that can inform initial planning of where zones can be established, and guidance for their management in the future. The analysis was undertaken across spatial scales including grid and municipality levels for bundling and, aggregated and disaggregated zones, which is informative for ES co-production, management, and governance since the activities are not constrained to single scales. The value of such research has important implications for BRs since organisations involved in their administration can act as bridges between academia and society, and amongst the actors involved in ES co-production, management, and governance.

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Author contributions JC conceived of the ideas for this study with input from AB and IM. JC and AB designed the PPGIS survey and collected the data. JC compiled all other data from secondary sources and did the mapping and analyses. JC wrote the first draft of the manuscript and AB and IM contributed to critical review and editing of the draft manuscript. All authors approved the final version of the manuscript.

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Declarations

Conflict of interest The authors declare no conflict of interest related to this research.

Ethical approval Ethics approval was obtained from The Norwegian Centre for Research Data (Naturgoder i Nordhordland UNESCO Biosfæreområde, Ref No. 657151) to undertake the survey used to collect data in this research.

Informed consent All participants gave consent in accordance with the conditions approved by The Norwegian Centre for Research Data prior to filling out the survey used to collect data in this research.

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Ambio

Electronic Supplementary Material
This supplementary material has not been peer reviewed.

Title: Integration matters: Combining socio-cultural and biophysical methods for mapping ecosystem service bundles

Authors: Jarrod Cusens, Alicia D. Barraclough, Inger Elisabeth Måren

Appendix S1: Methods for mapping ecosystem services

Cultural ecosystem services

We used an approach similar to that of Social Value for Ecosystem Services tool (SolVES; Sherrouse & Semmens, 2020). First, we calculated kernel density surfaces for each cultural ES, then normalised each of these by the maximum cell value among all kernel density surfaces. Second, we extracted the resulting maximum value for each kernel density surfaces. Third, we used Maximum Entropy (MaxEnt) to model probability distributions of each ES using 10 social-ecological landscape characteristics based on previous studies at a resolution of 250 m (Table S 1; Bagstad, Semmens, Ancona, & Sherrouse, 2017; Muñoz, Hausner, Runge, Brown, & Daigle, 2020; Sherrouse, Semmens, & Clement, 2014). We did not remove collinear variables because collinearity does not significantly affect MaxEnt model performance (Feng, Park, Liang, Pandey, & Papeş, 2019). For each MaxEnt probability output, we used the 'minimum training presence threshold' value below which we considered the ES value to be zero (i.e., no capacity to provide the respective ES). Finally, the probability distributions from the MaxEnt models for each ES were multiplied by the maximum kernel density values calculated in step one. All calculations were performed in *R* (R Core Team, 2021) using the *spatialEco* (Evans, 2020) package for kernel density estimates and the *dismo* package (Hijmans, Phillips, Leathwick, & Elith, 2020) for MaxEnt modelling. We used the *ENMeval* package (Kass et al., 2021; Muscarella et al., 2014) for model evaluation and model selection based on Area Under the Curve (AUC) and Akaike Information Criterion corrected for small sample sizes (AICc) respectively. All models performed moderately well (AUC > 0.78).

Table S 1. Data sources used in MaxEnt modelling of cultural ecosystem services from Public Participation GIS data.

Data	Description	Available from
LULC richness	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Agricultural land	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Forest	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Open land	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Water (including freshwater and ocean)	Calculated from union of AR5 and AR50 areal resources layers	AR5 (restricted access) and AR50 (open access) from https://www.nibio.no/
Hiking trails	Open street maps	https://www.openstreetmap.org/
Roads	N50 data layer	https://www.geonorge.no/
Buildings	N50 data layer	https://www.geonorge.no/
Elevation	Digital elevation model (DEM) at 10 m resolution	https://www.geonorge.no/
Slope	Calculated from the DEM at 10 m using the 'slope' function in the raster package in R (Hijmans, 2020)	https://www.geonorge.no/

Regulating and maintenance ecosystems services

Habitat quality

We mapped habitat quality separately for terrestrial and marine environments. To map habitat quality in terrestrial environments, we used an approach adapted from Ruas et al. (2021) that accounts for the capacity of different LULC types to support biodiversity, and additionally considered distance from anthropogenic infrastructure and landscape metrics including patch size and contiguity index. For marine environments we used a single value for the capacity of the habitat to support biodiversity and ecological condition potential from The Norwegian Water Resources and Energy Directorate, and additionally considered distance from anthropogenic infrastructure and density of shipping traffic. All landscape metrics were calculated using *landscapemetrics* (Hesselbarth, Sciaini, With, Wiegand, & Nowosad, 2019).

Water retention

Water retention was mapped using the Water Retention Index (Maes et al., 2015; Vandecasteele et al., 2018). This index is a composite indicator of that represents potential of the landscape to retain water and thus regulate potential flooding. The factors included in the indicator comprise retention in vegetation approximated by Leaf Area Index (Copernicus Global Land Services, 2019), retention in soil approximated by soil organic carbon content (Hengl et al., 2017), and retention in groundwater estimated from soil permeability (Panagos, Meusburger, Ballabio, Borrelli, & Alewell, 2014) and bedrock lithology (Gleeson et al., 2011). In addition, slope and soil sealing (Copernicus Global Land Services, 2018) are included since they both influence the capacity of water to be retained and to permeate the ground, respectively.

Avalanche prevention

We mapped avalanche protection capacity of forests using forest structure variables and topographic characteristics from Cordonnier, Berger, Elkin, Lamas, and Martinez (2014). First, we identified avalanche release zones as areas with slopes between 35° and 55°, similarly to Schröter, Barton, Remme, and Hein (2014), and identified areas in release zones that support forest. Then we calculated the Avalanche Protection Index of these avalanche release zones which considers slope and forest characteristics that contribute to reducing avalanche velocity including diameter at breast height, basal area, and dominant tree functional group as either evergreen (*Picea abies*, *P. sitchensis* or *Pinus sylvestris*) or deciduous (*Betula* spp.).

Global climate regulation

We mapped global climate regulation as total ecosystem carbon storage (ton/ha) including above- and below-ground biomass carbon, and soil carbon. Four spatial data layers were used for carbon stock estimation including AR5 and AR50 areal resources (Ahlstrøm, Bjørkelo, & Fadnes, 2019; Flo Heggem, Mathisen, & Frydenlund, 2019) for biomass carbon in non-forested systems, SR16 forest resources data (Astrup et al., 2019) for biomass carbon in forested systems, and SoilGrids250m (Hengl et al., 2017) for soil carbon. The spatial data from the AR5 and AR50 does not contain carbon estimates so we linked biomass carbon data to the LULC types from several sources (Bartlett, Rusch, Kyrkjeeide, Sandvik, & Nordén, 2020; de Wit, Austnes, Hylen, & Dalsgaard, 2015; Grønlund, Bjørkelo, Hylen, & Tomter, 2010; Grønlund et al., 2008).

Soil retention capacity

The capacity of vegetation to retain soil was modelled and mapped in a similar way to Quintas-Soriano et al. (2019) based on the Revised Universal Soil Loss Equation (RUSLE; Renard, Foster, Weesies, & Porter, 1991) which estimates the amount of soil lost or eroded from land. Inputs for the equation were rainfall erosivity (R; MJ/ha/mm/yr) calculated from mean annual rainfall (Foster, McCool, Renard, & Moldenhauer, 1981), slope length (LS; m) calculated from a digital elevation model, soil erodibility (K; ton/MJ/yr) calculated from SoilGrids250m data (Hengl et al., 2017) and a cropping factor (C; dimensionless) for each LULC type. Then, the capacity of vegetation to retain soil was estimated by calculating the difference between the result of the former from a hypothetical scenario with all cropping factor values set to one (i.e., no soil retention capacity).

Provisioning ecosystem services

Timber and firewood provision

We mapped timber and firewood provisioning capacity as the annual timber increment (m^3/ha/yr) of all forested areas within NBR. We used the species (pine, spruce or birch) and species specific site quality index from SR16 forest resources data (Astrup et al., 2019) to estimate timber increment based on the values from Tveite and Braastad (1981). The site quality index in the SR16 dataset is at a higher resolution (i.e., more site quality classes) than in the one of Tveite and Braastad (1981) so we used a simple linear model to interpolate annual timber increments to the SR16 data.

Water provision

The provision of freshwater was mapped using the Water Yield module in the *Integrated Valuation of Ecosystem Services and Tradeoffs* (InVEST) software (Sharp et al., 2020). The model calculates water runoff with a water balance equation using climatic variables of precipitation and evapotranspiration, soil variables of root restricting layer depth and plant available water content, and average rooting depth of LULC types present in the study area (Table S 4). Additional parameters included are the plant evaporation coefficient (*Kc*) and Z parameter which refers to the seasonal distribution of rainfall. We note that Sharp et al. (2020) advise that water yield data is best interpreted at the watershed or sub-watershed scale rather than the pixel scale. We acknowledge this as a potential issue, but we retain the pixel levels data for consistency with other ES indicators we have mapped.

Cultivated fodder production

We calculated the production of hay (ton/ha) from agricultural statistics and LULC data. First, we used national statistics to estimate the production of hay per hectare in the county in which NBR is located. Then we downscaled this data to grid cells based on the area of agricultural land used for hay production per gird cell, which includes fully- and surface-cultivated soils that can be harvested mechanically. Almost all areas with cultivated soils in NBR (over 99 %) are used for hay and grass production with very little cultivated land for other crops (Statistics Norway, 2019).

Table S2. Data sources used in this study for biophysical modelling and mapping of provisioning, and regulating and maintenance ecosystem services (ES).

ES category	ES	Method	Data source
Regulating and maintenance	Habitat quality	Phenomenological model	Forest data from SR16 forest resources data (Astrup et al., 2019). Non-forest LULC types from union of AR5 (Ahlstrøm et al., 2019) and AR50 (Flo Heggem et al., 2019) areal resources layers. Human infrastructure from N50 database (Kartverket, 2017). Marine ecological condition from The Norwegian Water Resources and Energy Directorate (NVE, 2015)
	Sediment retention	Revised Universal Soil Loss Equation	Rainfall erosivity (R factor) calculated from CHELSA annual rainfall (Karger et al., 2017a, 2017b) Slope length (LS factor) calculated from DEM using RSAGA package (Brenning, Bangs, & Becker, 2018) Soil erodibility (K factor) calculated using data from SoilGrids250m (Hengl et al., 2017) Cropping (C factor) estimated for each LULC from various sources
	Water flow regulation	Water Retention Index	Percent area of water body per catchment (Rwb) calculated from Retention in vegetation (Rv) calculated from Leaf Area Index data from Copernicus Global Land Services (2019). Retention in ground water (Rgw) was calculated from SoilGrids250m (Hengl et al., 2017) based on soil permeability data in Panagos et al. (2014), and bedrock data from the Norwegian Geological Survey and permeability from Gleeson et al. (2011) Slope factor (Rsl) calculated from DEM using RSAGA package (Brenning et al., 2018) Soil sealing (Rss) comes from Copernicus Global Land Services (2018).
	Global climate regulation	Sum of soil carbon and vegetation biomass carbon	Soil carbon data is from SoilGrids250m (Hengl et al., 2017). Forest biomass carbon is from SR16 forest resources data (Astrup et al., 2019). Non-forest LULC types from union of AR5 (Ahlstrøm et al., 2019) and AR50 (Flo Heggem et al., 2019) areal resources layers with carbon data

ES category	ES	Method	Data source
			from various sources (Bartlett et al., 2020; de Wit et al., 2015; Grønlund et al., 2010; Grønlund et al., 2008)
	Avalanche prevention	Avalanche Protection Index	Avalanche release sites were obtained from the Norwegian Water Resources and Energy Directorate (NVE, 2016), slope calculated from the DEM using the slope function in raster (Hijmans, 2020), and forest characteristics were taken from data from SR16 forest resources (Astrup et al., 2019).
Provisioning	Animal fodder production	Downscaled county level data to a grid based on agricultural land cover	Country level fodder production data from the Statistics Norway (2019) and agricultural land cover from AR5 areal resources layer (Ahlstrøm et al., 2019).
	Water supply	InVEST water yield model	Rainfall and evapotranspiration from CHELSA annual rainfall (Karger et al., 2017a, 2017b) Soil rooting depth and plant available water content from SoilGrids250m (Hengl et al., 2017) LULC types from union of AR5 (Ahlstrøm et al., 2019) and AR50 (Flo Heggem et al., 2019) areal resources layers. Watersheds and sub watersheds are from Norwegian Water Resources and Energy Directorate.
	Timber production capacity		Species specific site quality index data from SR16 forest resources (Astrup et al., 2019) and species specific annual tree increment data from Tveite and Braastad (1981).

Appendix S2: Differences in ecosystem service provision among zones

Zones in all habitats

When all habitats are considered together, cultural ES are generally higher in core vs. buffer and buffer vs. transitions zones except for wild plant, berries and mushrooms which was highest in the transition zone and higher in the core vs. buffer zone (Figure S1). Regulating and maintenance, and provisioning ES were generally highest in the buffer zone except for water retention which was highest in the transition zone and habitat quality which was highest in the core and transition zones (Figure S1).

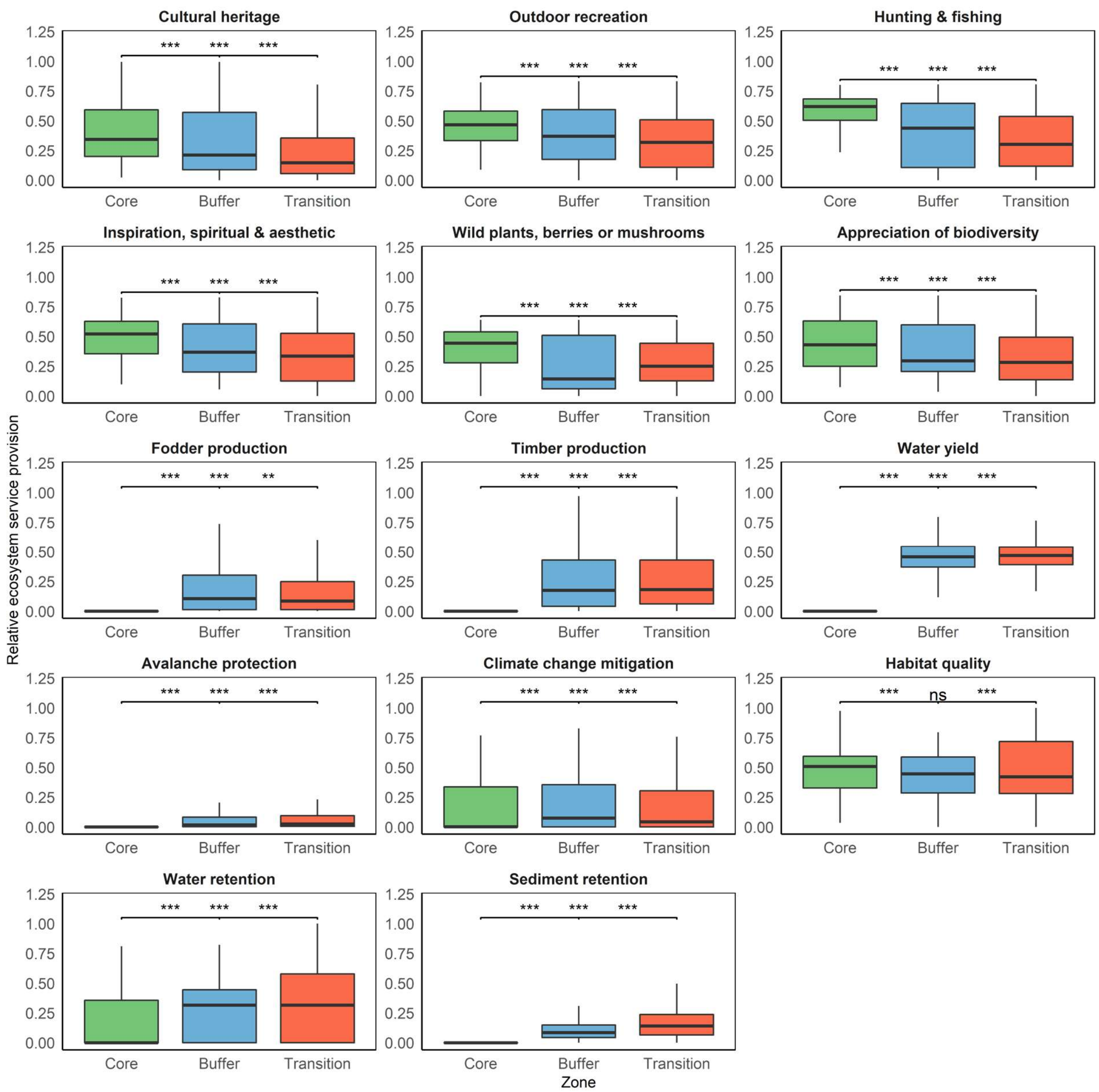

Figure S1. Boxplots of ecosystem service supply among the main zones in all habitats in Nordhordland Biosphere Reserve. Brackets and asterisks represent statistical tests of pairwise comparisons using Wilcox tests. ***, p < 0.0001; **, p < 0.001; ** p < 0.01, ‘, p < 0.05; ns, p > 0.05.

Zones in terrestrial habitats

In terrestrial cultural ES tended to be highest in the transition zone and not different core vs. buffer zone aside from outdoor recreation which was higher in the core vs. buffer zone (Figure S2). Regulating and maintenance, and provisioning ES were more variable.

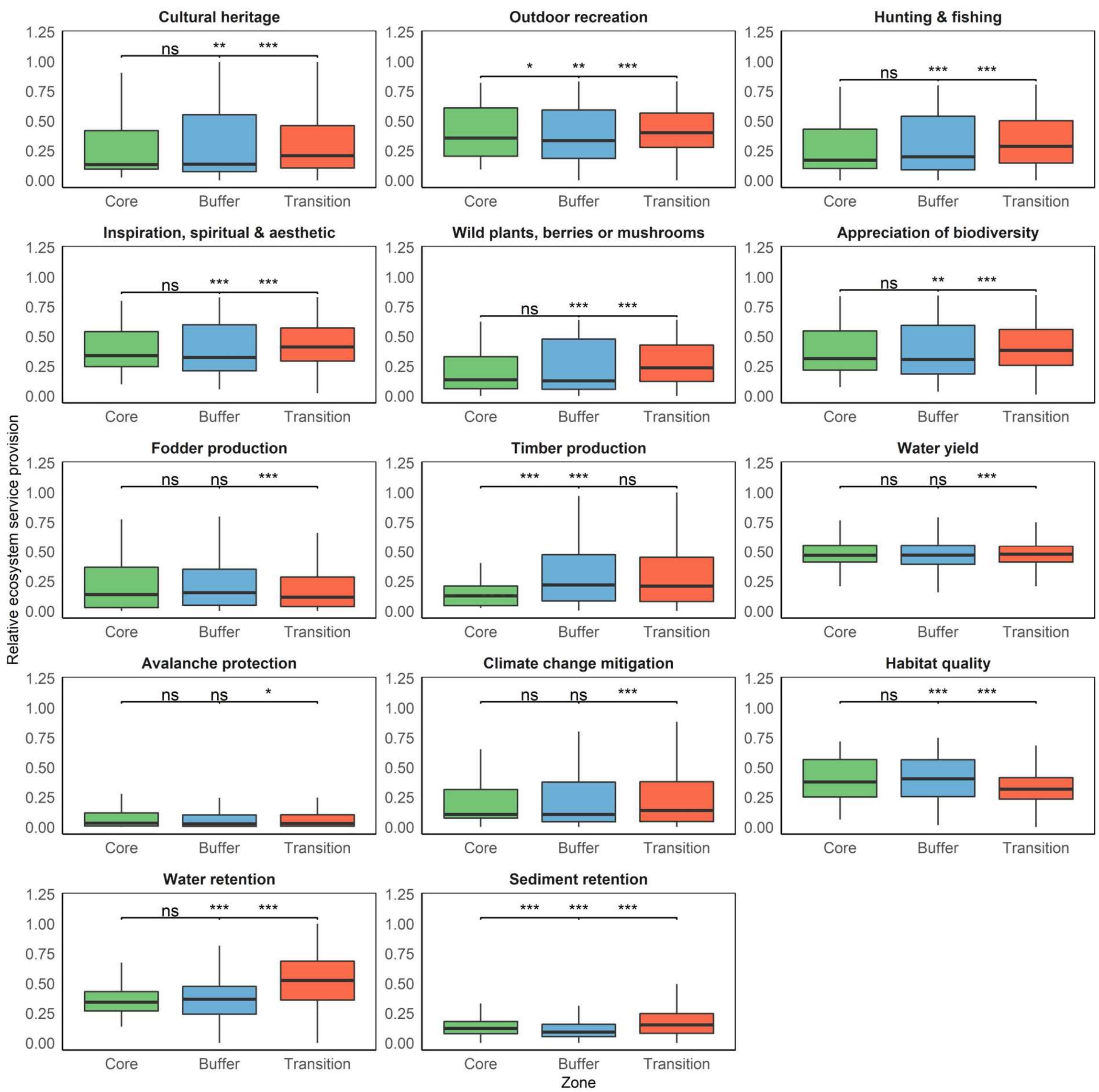

Figure S2. Boxplots of ecosystem service supply among the main zones in terrestrial areas in Nordhordland Biosphere Reserve. Brackets and asterisks represent statistical tests of pairwise comparisons using Wilcox tests. ***, p < 0.0001; **, p < 0.001; ** p < 0.01, ', p < 0.05; ns, p > 0.05.

Zones in marine habitats

In marine habitat cultural ES were highest in the core zone aside from hunting and fishing which was highest in the buffer zone (Figure S3). Likewise, climate change mitigation was highest in the core zone, while Habitat quality was highest in the transition zone (Figure S3)

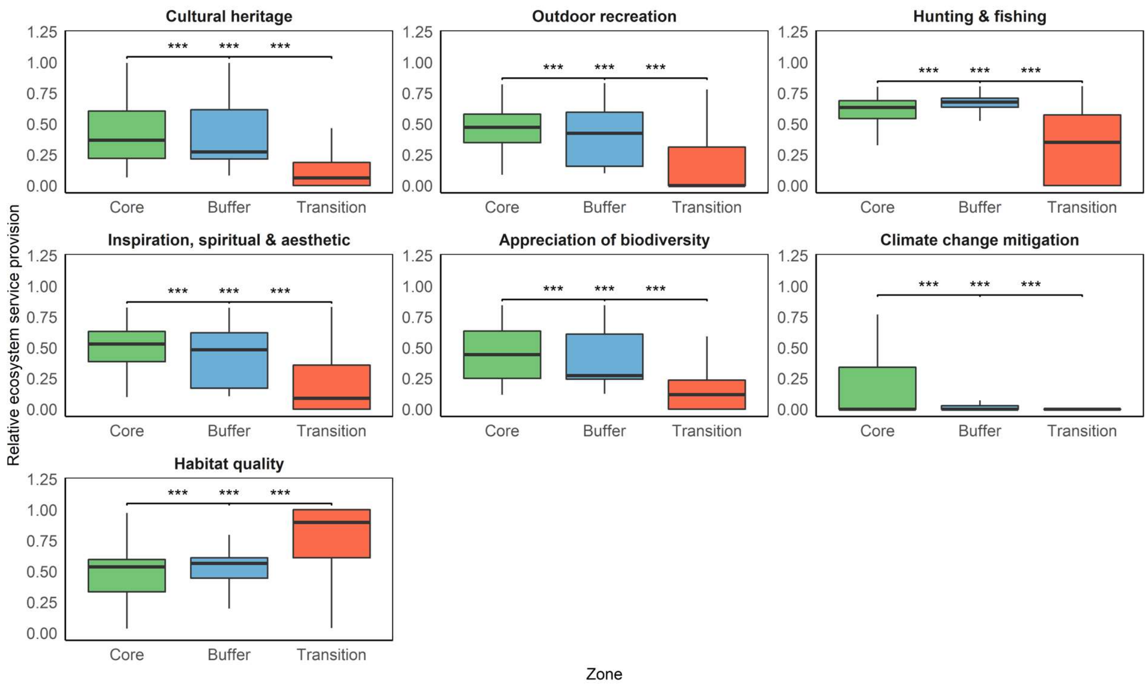

Figure S3. Boxplots of ecosystem service supply among the main zones in marine area of Nordhordland Biosphere Reserve. Brackets and asterisks represent statistical tests of pairwise comparisons using Wilcox tests. ***, $p < 0.0001$; **, $p < 0.001$; ** $p < 0.01$, ‘, $p < 0.05$; ns, $p > 0.05$. Note: Fodder production, water yield, timber production, wild plant, berries and mushrooms, sediment retention, water retention and avalanche protection are not shown since these ecosystem services are not provided by marine ecosystems.

Appendix S3: Land Use Land Cover composition of the ecosystem service bundles

The proportions of different LULC in each bundle at both scales were distinctive with Bundle 1 comprising a more even proportion of all LULC types, Bundle 2 being predominantly marine and Bundle 3 being predominantly ‘Open and sparse vegetation’ and forest (Figure S4). The main differences in LULC between the scales are the complete absence of inland terrestrial areas in Bundle 2 at the municipal scale and the lower proportion of marine areas in Bundles 1 and 3 at the grid scale (Figure S4).

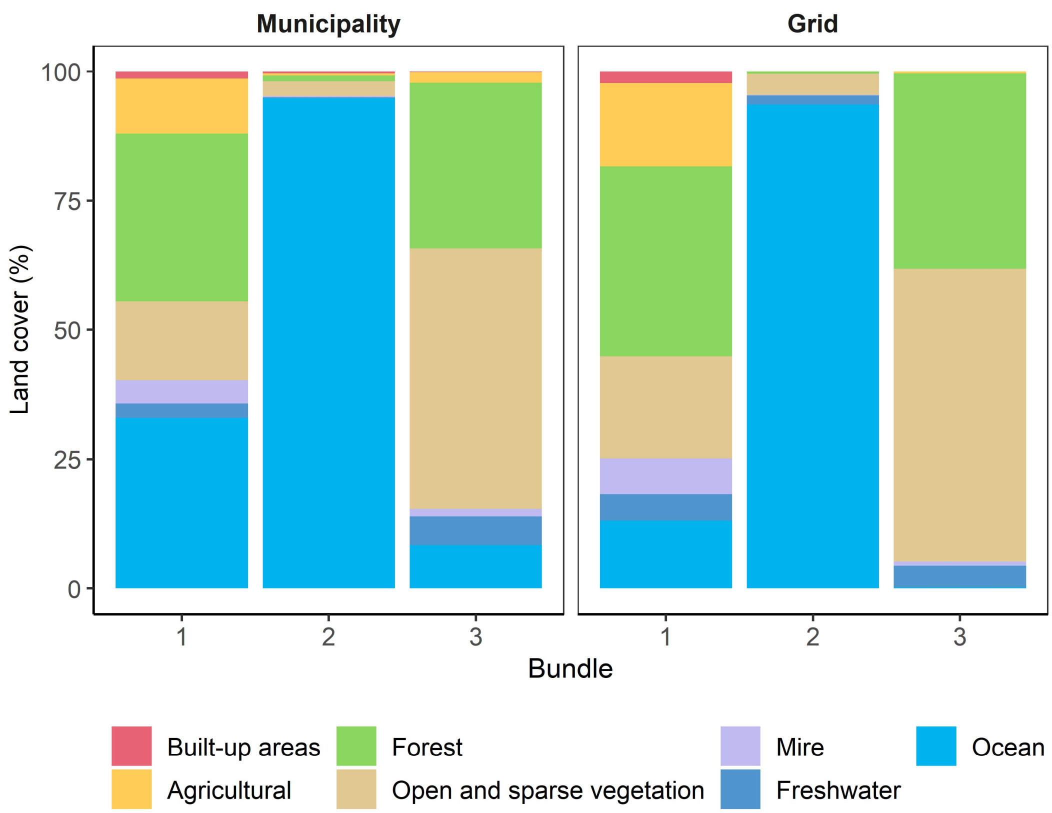

Figure S4. The proportions of the seven main land use-land cover types in each ecosystem service bundle at municipality and grid (250m × 250m) scales.

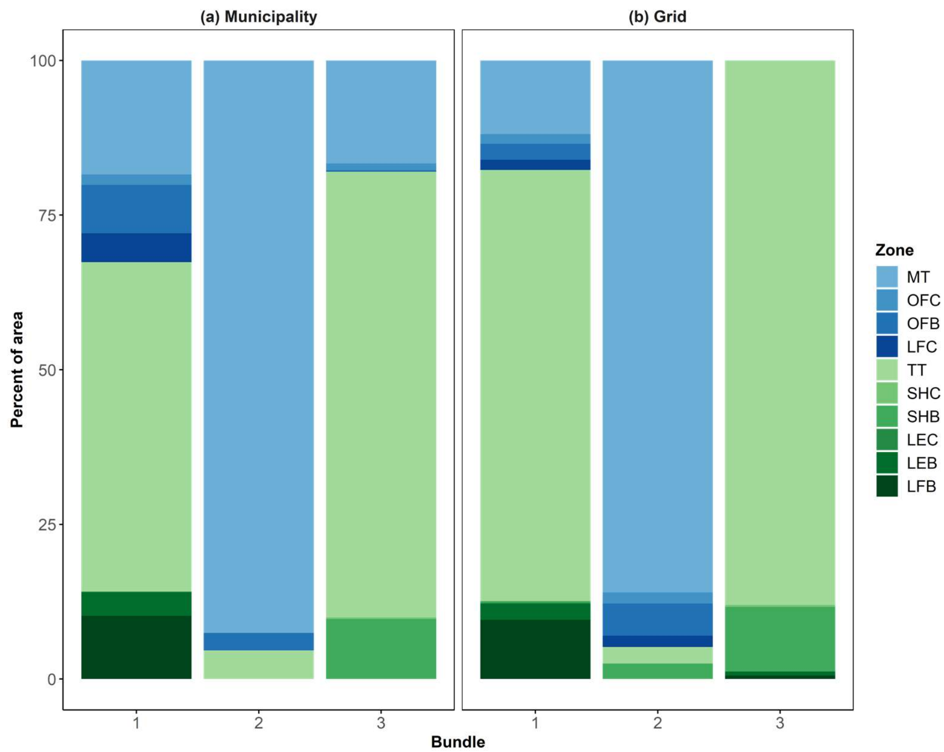

Figure S5. Relative areal proportion of zones within each bundle at the (a) municipality and (b) grid scales. Blue and green represent marine and terrestrial (and one freshwater) zones respectively. MT = Marine transition, OFC = Osterfjorden core, OFB = Osterfjorden buffer, LFC = Lurefjorden core, TT = Terrestrial transition, SHC = Stølsheimen core, SHB = Stølsheimen buffer, LEC = Loneelvi core, LEB = Loneelvi buffer, LFB = Lurefjorden buffer.

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PAPER III

Mapping stakeholder networks for the co-production of multiple ecosystem services: A novel mixed-methods approach.

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Heather burning for grazing maintenance at Lygra, Alver. Heather burning is an example of traditional ecological knowledge used in management of the cultural landscape. Photo: Jarrod Cusens

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Mapping stakeholder networks for the co-production of multiple ecosystem services: A novel mixed-methods approach

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ABSTRACT

Governance of ecosystem services (ES) requires an understanding of the complex dynamics of collaboration (and contestation) of multiple stakeholders and multiple ES. However, many studies consider only a few ES or stakeholder groups. In our work, we map the co-production of multiple ES by multiple stakeholders connected through ES governance networks. Through a unique combination of Public Participatory Geographic Information Systems (PPGIS), stakeholder focus groups, surveys, and social network analysis, we reveal insights on social-ecological fit of ES co-production across an area unified by a UNESCO Biosphere Reserve designation.

By overlaying relationships between stakeholders, multiple ES, and ES co-production networks, our results reveal gaps and mismatches in the ES governance system. We identified mismatches between those ES most valued by the region's inhabitants and those managed, governed and studied by relevant institutions and stakeholders. Cultural ES were the most highly appreciated by stakeholders, but social networks of cultural ES governance were the least densely connected, with highly influential stakeholders involved in cultural ES management (e.g., farmers), not well connected to the governance network. Thus, our findings point to a weakness in cultural ES governance and the need of incorporating cultural ES more clearly into natural resource management agendas.

Our results show the importance of mapping *what* is being discussed by *whom*, and that mapping environmental governance networks alone does not necessarily provide sufficient resolution to understand co-production of different ES. We confirm the difficulties of governing ES when the ES providers and/or beneficiaries operate at different or distant scales, the scale of ecological processes does not match management (e.g., in some regulating and maintenance ES), or stakeholders which are important in affecting ES provision are not involved in governance, resulting in social-ecological misfit. Lastly, our work confirms the broad array of research methods needed to capture the complexity of governing multiple ES.

1. Introduction

Human actions in the Anthropocene compromise the flow of essential benefits from nature to people (Díaz et al. 2019). Managing landscapes to ensure the sustained and resilient provision of Ecosystem Services (ES) has become a key focus area of national, regional and local initiatives, which have begun to mainstream ES throughout environmental policy and management (European Commission, 2019, Longato et al. 2021). Although ES-centred management has been proposed to ensure continuity of nature's contributions to people (Rozas-Vásquez et al., 2019), there has been limited theoretical and empirical work done on operationalizing ES-centred governance (Sattler et al. 2018). Navigating trade-offs between ES and disparate societal interests and values is no trivial task, and requires the development of frameworks and processes to resolve collective action dilemmas (Biggs et al. 2015, Lescourret et al. 2015, Loft et al. 2015, Barnaud et al. 2018).

Ecosystem services are coproduced by the interactions between ecosystems and people, and stakeholders in a landscape can be both beneficiaries and/or co-producers of ES (Spangenberg et al. 2014, Biggs et al. 2015, IPBES 2019). Governance and management-level decisions modify ES supply at various points of the ES cascade, for example through legislative changes in access, or through direct modification of

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supply through harvesting and/or management (Primmer et al. 2015). Past research has shown that ecosystem governance simultaneously addresses different types of ES, which results in a mixture of interacting institutions that should be adapted to different ES properties, resulting in good institutional or social-ecological fit (Falk et al. 2018). The subtractability and excludability of different ES, will determine the type of institution required to ensure their provision (Falk et al. 2018). For example, in the enjoyment of iconic landscapes it is hard to exclude others (low excludability) and the enjoyment does not get exhausted by others (low subtractability), whilst fodder production has high excludability and high subtractability. Although evaluations of use and direct modification relationships of provisioning ES are more abundant in the literature (Costanza et al. 2017), there is a less clear understanding of other ES, such as cultural ES (Blicharska et al. 2017). There may be competing interests for different ES resulting in management and/or use mismatches when one, or a particular set, of ES are prioritised leading to trade-offs among ES. Thus, ES governance must be understood as a complex network of overlapping institutions, which must work to harmonize diverse sets of ES. As such, networked or polycentric governance, a governance system with multiple, nested governing authorities at different scales, has been proposed to increase social-ecological fit and foster resilience of ES (Biggs et al. 2012). These forms of governance can enable participation and collaboration, building mutually reinforcing connections for ES governance between partners and stakeholders, rightsholders, the scientific community and the population at large (Connolly et al. 2014, Kotschy et al. 2015, Bodin et al. 2020).

Landscape multifunctionality has emerged as an idea that captures the capacity of landscapes to provide multiple ES simultaneously (Manning et al. 2018). Biophysical mapping of ES supply, ES flow, and ES demand have become increasingly common (e.g., Schirpke et al., 2019; Schröter, Barton, Remme, & Hein, 2014) and biophysical studies showing provision and demand of multiple ES have helped capture ecosystem multifunctionality, synergies and trade-offs between different ES (e.g., Raudsepp-Hearne et al. 2010, Parrott & Meyer 2012, Queiroz et al. 2015). However, reviews of ES governance literature (Sattler et al. 2018, Winkler et al. 2021) highlight that the extensive mapping of ES has not been matched with systematic mapping of governance (Primmer et al. 2021). In fact, social processes in general are considered underrepresented in the ES cascade framework, and we have limited understanding of how management and governance of landscapes affect ES at different points of the ES cascade (Spangenberg et al. 2014, Primmer et al. 2015). Although an increasing number of studies address this question (Connolly et al. 2014, Lienhoop and Schröter-Schlaack 2018, Vialatte et al. 2019), we are still far from matching the broad-scale understanding gained in many biophysical ES studies, approaching the complexity of multiple ES and multiple stakeholder groups at the same time (Howe et al. 2014). Mapping ES stakeholders, and their respective values, motives, and interests can help understand conflict and contestation over ES trade-offs and ES management decisions (Howe et al. 2014, Biggs et al. 2015).

Studies of ES as social-ecological phenomena must capture the complexity of relationships between multiple ES and multiple stakeholders. Network approaches have become a popular way to capture social-ecological systems properties, as complex adaptive systems which are constituted relationally through networks of actors and social-ecological relationships (Preiser et al. 2018). Social network analyses have revealed important insights on questions of collaboration and conflict in natural resource management, for example, by tying social network structure to environmental management outcomes (Bodin et al. 2020). Social network analyses have also contributed to the knowledge of social-ecological and institutional fit and mismatch, where institutional structures and networks should match the scales and processes of the ecological systems they govern (Bodin and Tengö 2012, Bodin et al. 2014, Guerrero et al. 2015, Dee et al. 2017). The use of social network analysis in the ES literature is however relatively underdeveloped (Connolly et al. 2014, Dee et al. 2017, Gaines et al. 2017, Schröter et al. 2018, Mason et al. 2020), and has often focused on a single ES (Meyer et al. 2019). Collaboration for ES governance and management can be facilitated by key bridging organizations in collaborative ES governance (Odom Green et al., 2015). UNESCO Biosphere Reserves (BR) have been proposed as examples of "round table" institutions which cross spatial and administrative boundaries and bring diverse stakeholders together (Odom Green et al., 2015, Schultz et al. 2018, Barraclough et al. 2021b). In this work, we study a BR in western Norway, Nordhordland UNESCO Biosphere Reserve, as an example of an institution that can cross jurisdictions and spatial boundaries to enhance social-ecological fit for networked ES governance. Developing simple tools to understand social-ecological fit, and mismatches between stakeholder interests and current governance priorities for multiple ES across collaborative platforms seems to be a vital step in integrating ES into decision making.

In this study, our key objective is to comprehensively map the social dimensions of the ES cascade and understand how multiple stakeholder groups participate in the co-production of multiple ES. Our study uses a simple mixed-methods approach to outline the relationships between stakeholder groups and ES ("stakeholder-ES relationship bundles") and stakeholder social networks to understand how natural resource management overlaps with ES governance. By systematically mapping stakeholders' relationships to ES and to each other, we aim to show the networks on which ES supply depends across multiple municipalities unified by a UNESCO BR designation. Our key questions are (1) How are different co-production relationships (management, governance, knowledge production and valuation) connected to bundles of ES? (2) What stakeholders are involved in the management and governance of multiple ES? (3) What is the structure of the ES co-production network and how does it differ for different ES classes (provisioning, cultural and, regulating and maintenance)?

2. Material and methods:

2.1. Methodological framework and considerations

Our methodology is situated in the importance of considering synergetic bundles of ES rather than single selected ones (Malmborg et al. 2021). We follow a sustainability science approach, by which we combine different methods to produce actionable knowledge which contributes to sustainability transformation – thus taking a normative stance in our work (Miller et al., 2014; Mach et al., 2020).

We use a mixed-methods approach to understand how natural resource management overlaps with the governance and co-production of multiple ES, by seeing ES co-production as a network where actors interact with ES via different kinds of relationships: benefit and societal demand, management, governance, and knowledge production (Fig. 1). We approach each of these with specific analytical tools (Fig. 1, blue squares): (1) A PPGIS survey to understand stakeholder valuation of ES benefits; we used PPGIS because it captures social-cultural values for ES (Brown and Weber 2011, Scholte et al., 2018) (as opposed to biophysical values), (2) a survey of governance, management and knowledge production relationships of key stakeholders involved in networked governance to map stakeholder involvement in the co-production of different ES and, (3) a social network analysis, to understand the structure of the ES networked governance and the relationships between different stakeholder groups involved. We integrate our analysis the existing frameworks on ES governance and institutional mapping of Primmer et al. (2021).

2.2. Case study

The study took place in the Nordhordland Biosphere Reserve (NBR), Norway's first and only UNESCO Biosphere Reserve declared in 2019 (Fig. 2). Nordhordland itself was a historic province that no longer holds administrative status and now encompasses 9 municipalities. NBR is managed by a municipally funded company supported by those 9

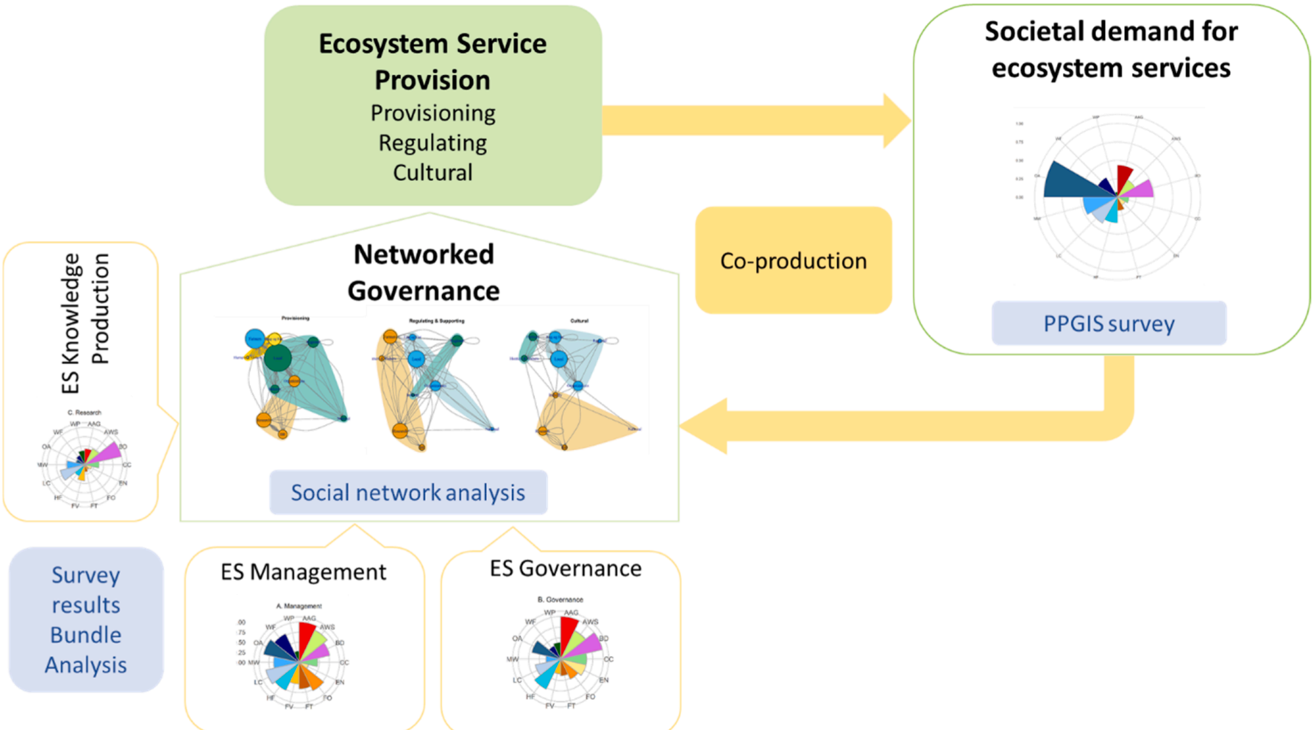

Fig. 1. Diagram depicting our methodological and conceptual approach to the institutional and stakeholder dimensions of Ecosystem Services (ES), modified from the framework by Primmer et al. (2021). The analysis tools employed to approach each are shown in blue squares: ES-stakeholder relationships of governance, management, and knowledge production (flower diagrams), social valuation of ES (through PPGIS), and the structure of ES networked governance (social network analysis).

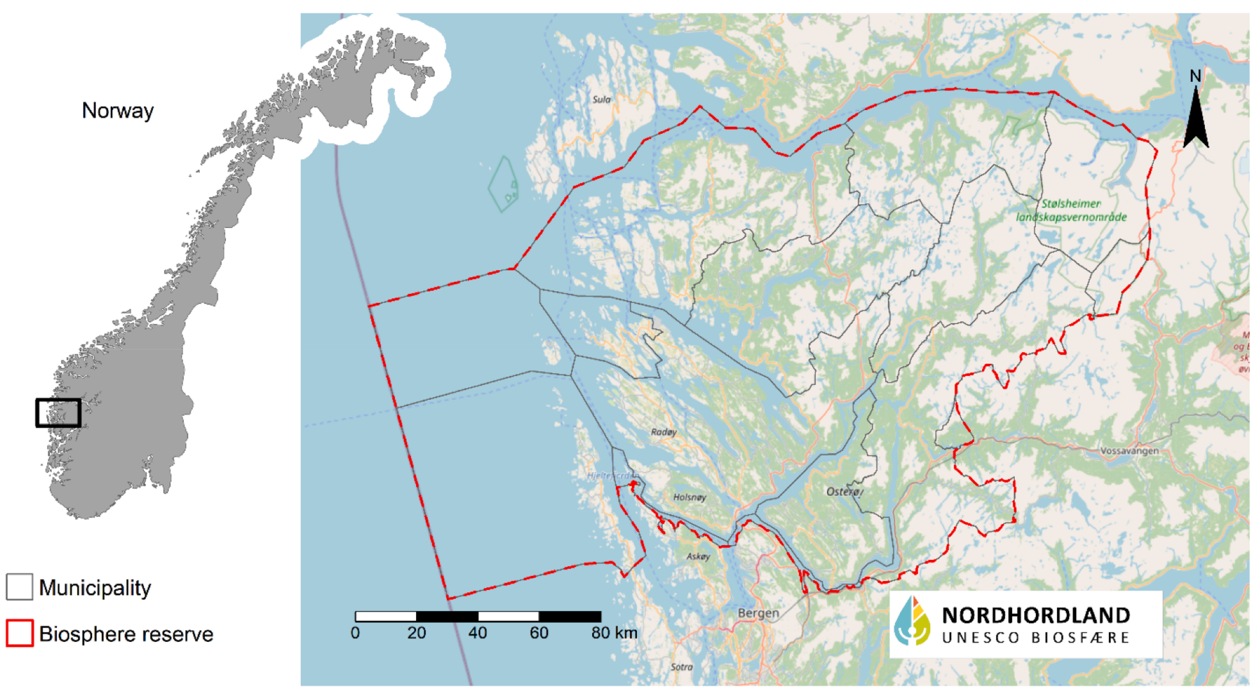

Fig. 2. The location of Nordhordland Biosphere Reserve on the West coast of Norway. Basemap provided by Open Street Map.

municipalities, and is still in its initial phases of establishment, with its organizational structure still under development. This case study was chosen because it constitutes a comparatively large region (6,698 km^2) where municipalities are unified by a UNESCO designation which is intended to foster collaborative environmental governance (see Introduction).

NBR represents a typical coastal and fjord landscape of Western Norway, extending from the most western archipelagos through deep fjords into high mountain areas inland. There is one Protected Landscape Area (Stølsheimen, 37.5 ha) and one marine protected area

(Lurefjorden and Lidåsosane, 6.9 ha) in NBR, in addition to several smaller Nature Reserves in the region. The main economic activities and sources of employment are in public services and industry (mainly connected to petroleum). Hydroelectricity production is also a significant source of income for local municipalities with a high proportion of rivers having energy production infrastructure (Kaland et al., 2018). Agriculture is of cultural and historical importance, although of minor economic importance, where the size of holdings is on average small (14.5 ha) and with farmers often relying on government subsidies. Main farming activities are cattle holding, mainly cows for milk and meat, sheep for wool and meat, and goats for milk and meat (Måren et al. 2022). Outfield grazing is historically important in the region and in maintaining the cultural landscape (Vandvik et al. 2014). Vegetable production is of low importance although it is currently being encouraged by several market-garden production projects. Forestry is of growing importance, with many of the plantations established in the 1950s, predominantly on private land, now reaching harvest maturity. Although there are no state-owned forests in NBR, there is a large association of private forest owners contributing to management and forestry road development.

2.3. Survey design and data collection

The online survey was a conditional branched survey, with two distinct sections: 1) a PPGIS survey aimed at the public where respondents were provided a list of 12 different ES (see Supplementary Material) to choose from at will and then place on a map of the BR where they received this ES (Cusens et al. 2022), and 2) a set of questions aimed only at key stakeholders which were selected through conditional questions asking if they were involved in natural resource management in the region. We defined key stakeholders as those working in agriculture, forestry, hunting or fishing, and any form of cultural, biocultural or natural resource-related management, governance, industry or research. This section of the survey contained questions on stakeholder roles and asked participants to identify their relationship to a list of 14 ES as either "direct management or modification" (hereon referred to as "management" relationship), "enforcement, regulation or legislation" (hereon referred to as "governance" relationship), or" knowledge gathering or research" (hereon referred to as "research") (modified from Alonso Roldán et al. 2015). This section also contained questions relevant to the social network of stakeholders working in natural resource management in NBR, following an Organizational Network Analysis (ONA) method (Eisenberg and Swanson 1996), where the unit of analysis is stakeholder interest groups. Participants were asked to identify general stakeholder classes with whom they communicated with on a regular basis to achieve their natural resource management goals. Respondents could choose from a list of 10 stakeholder classes (see Table 1) and place an icon of them on a map in the municipality or area this stakeholder was based (Barraclough et al. unpubl.). For each selected stakeholder, participants were asked to complete an open question on what their communication was about in relation to the landscape of NBR and rate how effective the communication was to achieve their work related to nature.

The survey went through different stages of participatory design with local stakeholders. Firstly, the list of ES was chosen in consultation with the BR organization's documents, primarily the UNESCO Biosphere Reserve candidacy application (Kaland et al., 2018), while the list of relevant stakeholder classes was elaborated from the BR's stakeholder analysis documents part of their start-up strategy process (Table 1). A focus group session with representatives of the local municipalities (planning, agriculture, and environment), agriculture advisories and the BR organization allowed us to refine and complete the list of ES and relevant stakeholder classes. The list of ES provided to the general public in the PPGIS exercise (12 ES), and to core stakeholders in the management-oriented exercise (14 ES), differed slightly as after focus group discussions we chose to adapt the ES to each context (see also Supplementary Material & Cusens et al. 2022). During this process, we decided to have 12 ES categories for the general public, but two additional ES categories for the key stakeholder evaluation ("fodder" and "fruit and vegetables", Appendix Table 1) since they were considered of particular importance by focus group participants.

Table 1
Survey participants (n = 313) who responded to the survey by stakeholder class in the Nordhordland Biosphere Reserve, those marked with an * asterisk were key respondent classes.

Stakeholder Class	Participants (n)	Description
General public	111	General public who only participated in the PPGIS section of the survey
Farmers*	72	Farming union representatives, individual part- and full-time farmers
Hunters and Fishers*	21	Hunting and fishing organization representatives and individual hunters and fishermen
Industry*	11	Representatives of the aquaculture industry, oil industry, energy industry and forestry
Business*	21	Consultants engaged in environmental monitoring and mapping, tourism businesses, gastronomy related businesses, small-scale timber and wood businesses
"Lag og foreiningar" (clubs and community groups)*	17	Small (neighbourhood or local) community clubs, groups, and associations for local culture, environment, nature, or outdoor pursuits.
Organizations*	14	Larger regional scale organizations and non-profits for the preservation of cultural landscapes, nature conservation, and cultural heritage
Local Government*	22	Local municipality heads of agriculture, forestry, landscape planning, culture and general coordination (in the case of very small municipalities)
National Government*	2	Coastal management, environment office
Regional Government*	7	Regional government representatives for nature management, agriculture, culture, education and general coordination
Scientist/Researcher*	11	Researchers from higher education institutions and research centres working on environmental science, ecology, eco-economics and marine research
Other*	4	Community members, landowners, and foragers
Total	*313*	*All participants*

We launched the online survey in February 2020 which was open for six months. The survey was sent out in an email campaign to a list of 224 key stakeholders, with an initial invitation, a midway reminder, and a final invitation. The email list was compiled via grey literature review, website searches, and consultation with the BR organization. The stakeholder list contained key organizations, local community groups, farming unions (and their mailing lists), relevant businesses, and higher education institutions and research institutions connected to natural resource management, in addition to representatives of relevant office sections at each of the 9 local municipalities, and regional and national government offices. The emails contained an invitation for forwarding the survey, thus in addition to directed sampling, we also engaged in snowball sampling (Biggs et al. 2021). After the last email reminder, we consulted the list of participants to identify missing key respondents, who were invited to participate via phone calls. The survey was also shared with the general public via several articles and advertisements in three local newspapers, a workshop campaign in which we visited local libraries in all 9 municipalities and helped locals fill in the PPGIS component of the survey, and a social media promoted add campaign through the NBR social media pages (more in Cusens et al. 2022).

A total of 313 participants completed at least one of the two survey components. The general public, who only completed the PPGIS portion of the survey, totalled 111 respondents. Key respondents, who completed the questions related to natural resource management, totalled 202 respondents (111 male, 89 female, 2 other/prefer not to say). Key respondents represented 75 unique organizations, clubs, unions, government offices and other collective entities (Table 1), as well as individual farmers and hunters.

2.4. Ecosystem service and stakeholder-Ecosystem service relationships data analysis

To ascertain links between stakeholders and the different ESs, we tabulated the responses to the questions on relationships between stakeholders and ES. On the one hand, all positive responses to an ES were summed for the different relationship categories of modification and management, governance, and research, and total sums were scaled between 0 and 1 within each relationship category, from which ES-relationship flower diagrams were constructed. On the other hand, to show connections to ES within each stakeholder class, we summed all positive ES responses counting maximum one link as a positive response to any relationship category, and then divided the sum by total participants of each stakeholder class to create a weighed proportion, from which ES-stakeholder flower diagrams were constructed. We used flower diagrams to represent the relationships where different connections to ES were shown for either stakeholder or relationship type (Foley et al. 2005). Stakeholder-ES bundles were then analysed via *k-means* clustering to test for similarities between bundles (Raudsepp-Hearne et al. 2010), with the *kmeans* function in R (R Core Team, 2020). To calculate the benefit relationship as shown by ES public valuation, we summed all points resulting from the PPGIS mapping exercise and ranked the ES by total number of points chosen (Brown and Weber 2011), and then scaling between 1 and 0.

2.5. Social network construction and analysis

We constructed a social network based on the responses of 126 participants whose social network responses were deemed valid via a manual data check. To be deemed valid, respondents needed to have answered at least one open question per chosen social connection and chosen at least two different social connections. Participants placed a total of 506 stakeholder points, an average of 4 connections per person. For the purposes of this work, it was sufficient to generate a single mode directed network aggregated by stakeholder role. To do this, first we generated a directed matrix whose first dimension was “link givers”, which were the participants who had placed stakeholder dots on the map, and the second dimension were “link receivers”, who were the stakeholders who participants said they were talking to. We then aggregated each dimension by stakeholder class, summing all links and generating link weights which were divided by the number of total participants (“link givers”) of each class. Stakeholder classes were aggregated across municipalities (see Supplementary Material Table 1). Average connection efficiency between stakeholder classes was averaged across the same link type and incorporated as a second-dimension link weight.

Three additional social networks were constructed for three main ES categories of provisioning, regulating and maintenance, and cultural ES. Supporting and regulating and maintenance ES were pooled into one class, and we included biodiversity as we considered it analogous to the ES “maintenance of habitats” as per the CICES classification 5.1 (Haines-Young and Potschin 2018). Node links for each of these networks were obtained by qualitatively coding the responses to the open questions that asked participants which topics they discussed with each of the actors they had selected in the social network questions of the survey (for more details of coding criteria please see Supplementary Material). Whenever an ES was mentioned, the response was coded to the appropriate 14 ES categories as a 1 (mentioned, a link), or a 0 (not mentioned, no link). The links for the 14 ES were summed to yield total link weights for each of the three ES categories. This initial multiplex network of three different link types and identical nodes (Baggio et al. 2016) was then subset to yield three individual networks for analysis. R package “igraph” was used for network manipulation, visualization, and analysis (Csardi and Nepusz, 2006). For all networks we calculated measures of network density, centrality, maximum path length and betweenness. We calculated community clusters via the optimal modularity clustering method (Brandes, 2007), using the *cluster_optimal* function in *R*, which calculates the optimal community structure for a graph, in terms of maximal modularity score. All data construction, manipulation and analyses were done in R (R Core Team, 2020).

3. Results

3.1. Ecosystem service relationships: Management, governance, research, and benefit

Respondents who identified themselves as “governing” ES (Fig. 3) predominantly chose biodiversity, clean air, water, and soil, energy, climate change mitigation, outdoor activities, and hunting, whilst the least chosen ES were extreme weather event protection and wild food provision. The ES most chosen as “directly managed” were the provisioning ES of livestock agriculture, fodder and forestry, the regulating and maintenance ES of clean air, water, and soil, and biodiversity, and the cultural ES of outdoor activities, local culture, hunting and fishing, and wild food (Fig. 3). The least directly managed were extreme weather event protection and energy. The most researched ES was biodiversity, followed by local culture (Fig. 3). Local municipality representatives and other stakeholders (e.g., farmers) did not identify as researching or gathering knowledge on almost any of the ES that they identified as managing or governing.

Benefit relationships were assessed through the PPGIS public valuation component of the survey, which had 313 participants who mapped 3,215 ES points. The most mapped ESs were outdoor recreation and biodiversity appreciation, and the lowest were protection from weather events and energy production. When comparing mismatches between ES governance and management relationships and public ES benefit relationships by comparing the total number of times each ES was selected per relationship type (see Supplementary Material Fig. 1), the highest ranked ES in governance and management was clean air, water and soil, which was only the seventh most mapped ES in the PPGIS mapping. In addition, mental wellbeing was the third most mapped by the public but came ninth in the governance ranking. Both the benefit and the governance-related rankings had outdoor activities, biodiversity, and hunting and fishing in their top five ESs. In addition, protection from extreme weather events, climate change mitigation and energy production coincided in being the least mapped by the public and the least covered by co-production links (Supplementary material).

Cluster analysis of the public ES valuation resulted in four distinct actor groups based on the number of each ES that they mapped in the PPGIS and their self-reported role (total within SS = 2.4, total SS = 8.4, between SS / total SS = 70,9 %). *Group 1* was constituted by farmers and foresters, characterized by high valuation of agricultural and forest products, local culture, biodiversity, and outdoor recreation. *Group 2* was constituted by actors who identified as entrepreneurs and valued agricultural products, and forestry and timber production, with relatively low valuation of commonly mapped cultural ES like outdoor recreation or local culture. *Group 3* was made up of students, scientists and researchers, and tourists, characterized by high values for biodiversity and outdoor recreation. Finally, *Group 4* was made up of all remaining stakeholder classes (business, cabin owners, hunters and

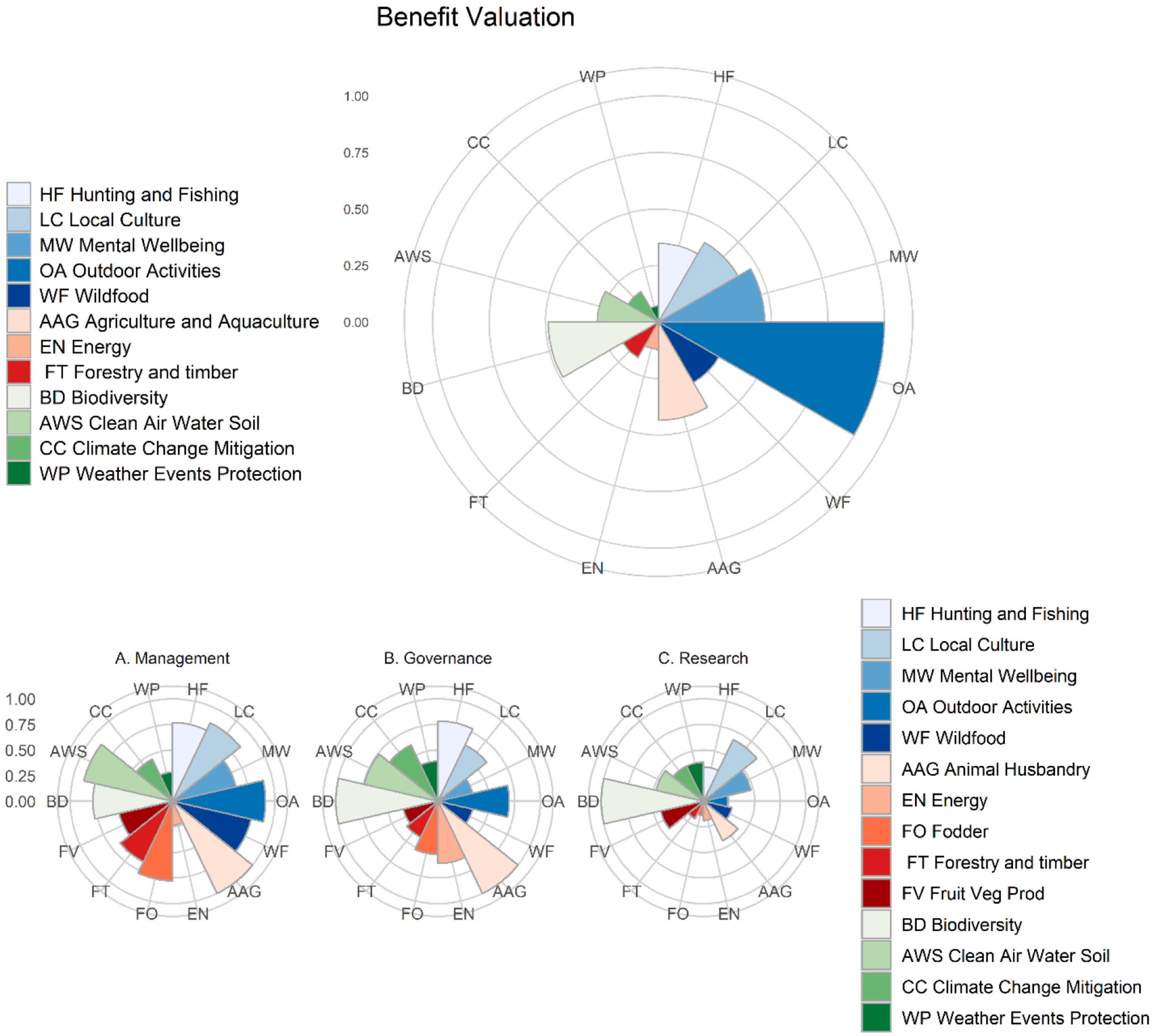

Fig. 3. Relationships to the ecosystem services categories across Nordhordland Biosphere Reserve key stakeholders. Top panel: General public valuation of ecosystem services as obtained by a participatory geographic information system (PPGIS). Bottom panel: Ecosystem services connected to key stakeholders through management (A), governance (B) and research or knowledge gathering (C). Ecosystem services categories of PPGIS valuation and governance categories were adapted to each context.

fishers, industry, inhabitants, government workers, NGO workers, part-time inhabitants, and voluntary workers), whose ES values were dominated by cultural ES appreciation, particularly outdoor recreation, mental wellbeing, local culture and hunting and fishing, in addition to biodiversity appreciation (Supplementary Material Fig. 2).

3.2. *Key stakeholder ecosystem service co-production bundles*

Farmers, fishers, and hunters all identified themselves as highly connected to provisioning ES, like animal husbandry, fodder, and timber production (in the case of farmers), and hunting and fishing in the case of hunters and fishers (Fig. 4). All three groups also identified themselves as connected to regulating and maintenance ES, such as clean air, water, and soil, biodiversity, and to cultural ES like outdoor activities, wild food, mental wellbeing, and local culture, especially farmers and fishers for the latter. Businesses were connected sparsely to all ES, but predominantly to biodiversity, and cultural ES such as outdoor activities, mental wellbeing, and hunting and fishing. Local community groups' work was connected predominantly with cultural ES such as outdoor activities, local culture, and mental wellbeing. Local organizations had similar ES connections, but a higher proportion worked in connection with biodiversity (Fig. 4).

Researchers were mainly concerned with biodiversity, clean air, water and soil, and climate change mitigation. Local government was evenly connected to all ES, but predominantly to biodiversity, clean air, water and soil, climate change mitigation, and cultural ES like outdoor activities, local culture and hunting and fishing. The regional government was similar to local government, but with a higher proportion connected to provisioning ES like animal agriculture, and fruit and vegetable production. National government was connected to regulating and maintenance ES of biodiversity, clean air, water and soil and climate change mitigation. Overall, very few key stakeholders saw themselves in connection with climate change mitigation, except industry, and the local and national government (Fig. 4). A *k-means* cluster similarity analysis showed four clusters, where the *ES Cluster 1* contained business, industry, *lag og foreiningar*, local government and organizations. *ES Cluster 2* was farmers and regional government. *ES Cluster 3* was hunters and fishers, and *ES Cluster 4* was national government, scientists and

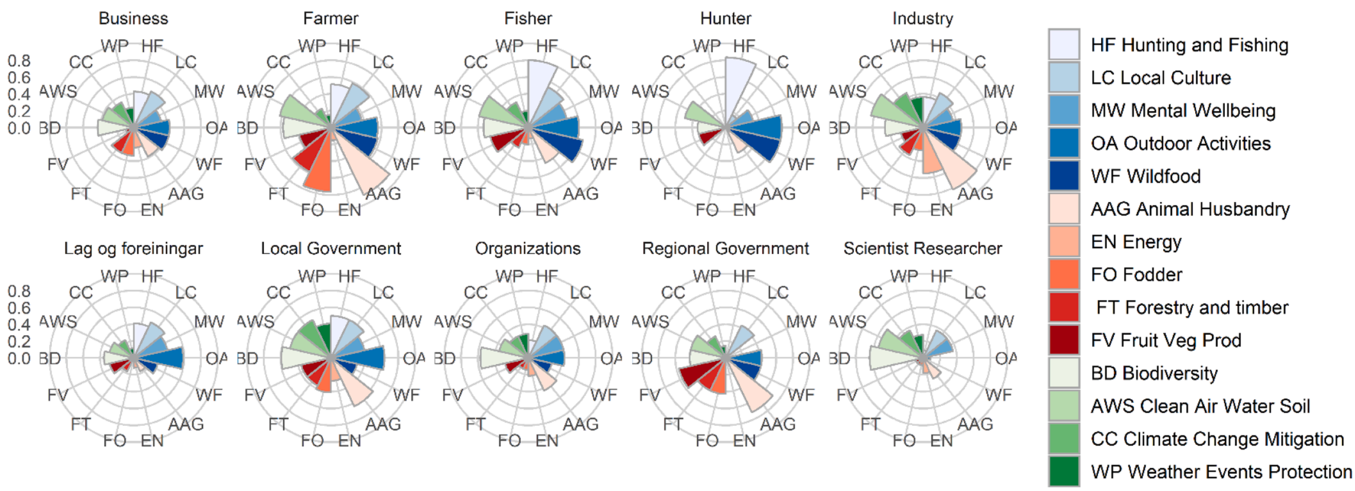

Fig. 4. Ecosystem Service flower diagrams for each key stakeholder class, showing the total proportion within each stakeholder group that identified a management, governance or knowledge gathering relationship to the different Ecosystem Services. The Biosphere Reserve organization was included in the group “Organizations”, and “lag of foreiningar” encompasses local groups, clubs, and associations.

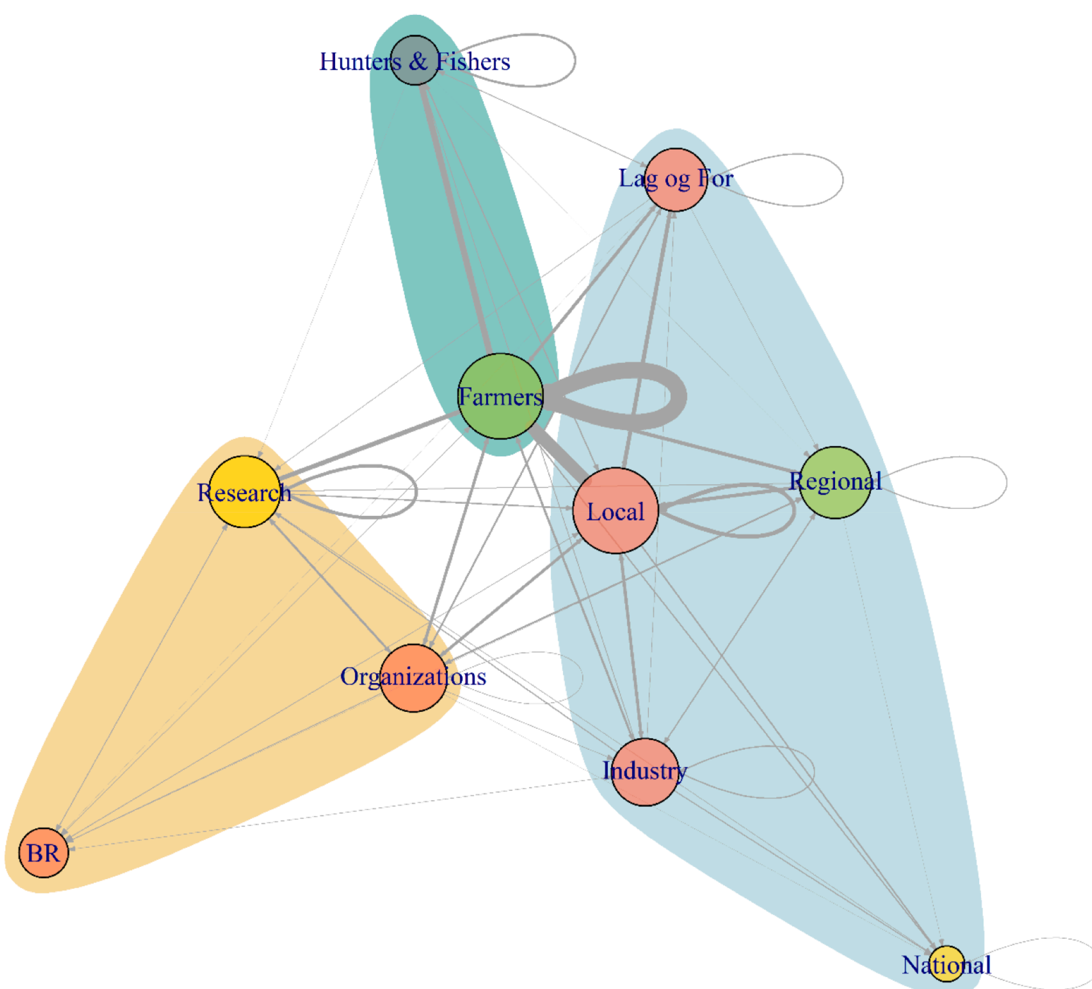

Fig. 5. Simplified natural resource management social network of the Nordhordland UNESCO Biosphere Reserve. Nodes are marked with the stakeholder classes outlined in Table 1 where BR stands for Biosphere Reserve organization. Node colours show the ecosystem service co-production cluster (Cluster 1, pink; Cluster 2, green; Cluster 3, grey; Cluster 4, Yellow; see Results ES Cluster1-4). Large colour polygons show stakeholder membership to a network community calculated with a network modularity cluster analysis.

researchers (total within SS = 2.3, total SS = 7.16, between_SS/total_SS = 66.7 %) (Fig. 5, node colours).

3.3. Social networks of ecosystem service management, and governance

Network nodes with the highest degree centrality (both out- and indegree centrality) were farmers and local governments (Farmers = 19, Local Government = 19) (Fig. 5). Betweenness centrality, which is thought to be a measure of "brokerage" was highest for the BR organization (29.18) and regional government (19.33). Highest link weight in the network was found between farmers and (1) other farmers, (2) local governments, (3) hunters, and fishers. Highest communication efficiency was between organizations and farmers (both directions, non-significant), whilst the lowest was between local organizations, and local and regional governing bodies (directed, Kruskal-Wallis p-value < 0.01). The results of the network modularity cluster analysis showed that there were three distinct communities. *Community 1* was formed by farmers, and hunters and fishers, *Community 2* was formed by *lag og foreiningar*, industry, and local, regional and national governments, and *Community 3* was formed by organizations, researchers, and the BR organization (optimum clustering modularity score = 0,38). No single social network community contained representatives of all ES-clusters, where the most diverse community was the largest (Cluster 2), which contained three different ES-clusters in it (richness = 3) (Fig. 5).

Multiplex ES social network construction (a network showing different link types) revealed three distinct social networks for provisioning, regulating and supporting, and cultural ES (Fig. 6). The provisioning ES network was the most like the overall social network, with high density (density = 1.4), and similar node-level measures with highest degree centrality of local municipalities (centrality = 57) and farmers (centrality = 41), and highest betweenness centrality of local municipalities and local associations (betweenness = 10.79 and 9.4 respectively). The provisioning ES network had the same stakeholder community membership in the clustering analysis (clustering score = 0.59), except farmers did not cluster with any other community.

The networks for regulating and supporting, and for cultural ESs,

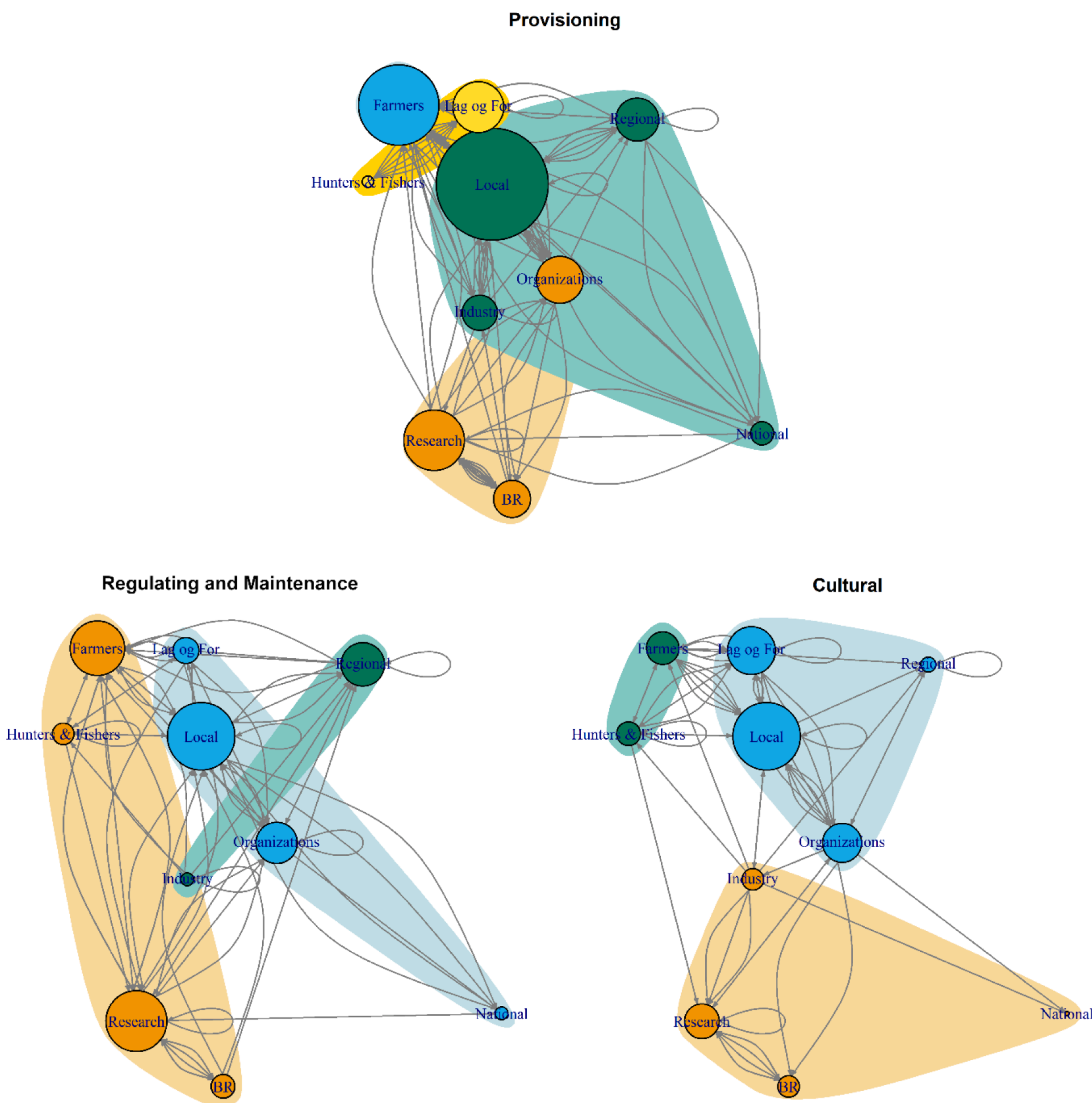

Fig. 6. Social networks for all evaluated Ecosystem Services (ES) grouped into provisioning, regulating and maintenance, and cultural ES. Size of node is a measure of centrality, both node and polygon colour show node community membership based on a network modularity cluster analysis.

showed a distinctly different network measure and community composition to the overall and provisioning networks (Fig. 6). Regulating and maintenance ES had lower network density than the provisioning network (0.93), whilst the cultural ES network had the overall lowest network density (0.79) of all the ES networks. Both the regulating and maintenance, and cultural ES networks also showed the highest degree centrality for local municipalities (centrality = 31), similar to the overall and provisioning networks, but differed in showing the second highest degree centrality for researchers (centrality = 28), in the case of regulating and maintenance ES network, and local associations and clubs (centrality = 22), in the case of the cultural ES network (Fig. 6). Betweenness centrality was highest for farmers in the case of regulating services (betweenness = 12.3), and for local organizations in the case of cultural services (betweenness = 36.4). Community network modularity cluster analysis also showed that the nodes of regulating and maintenance, and cultural ES networks clustered into very different communities. Regulating ES social network nodes clustered into communities *Regulating 1*: farmers, hunters and fishers, researchers and scientists and the BR organization, *Regulating 2*: local associations, local government, organizations and national government, and *Regulating 3*: industry and regional government. Cultural ES social network nodes clustered into *Cultural 1*: farmers, and hunters and fishers, *Cultural 2:* local associations, local government, organizations and regional government, and *Cultural 3:* industry, researchers and scientists, the BR organization and the national government.

4. Discussion

Landscape multifunctionality has become an important multidisciplinary research area investigating the provision of multiple ES in "shared landscapes" (Plieninger et al. 2013, Manning et al. 2018, Kremen and Merenlender 2018, Fagerholm et al. 2019). However, we still lack an in-depth understanding of the governance of multiple ES, and how to manage trade-offs between different ES and diverse stakeholder interests (Albert et al. 2017, Sattler et al. 2018, Quintas-Soriano et al. 2019, Primmer et al. 2021, Winkler et al. 2021). We systematically mapped different kinds of relationships (benefit, management, governance, and research) between stakeholders and ES, revealing the co-production networks on which ES provision depends, across a large region unified by a UNESCO Biosphere Reserve (BR) designation. We show that mismatches exist between stakeholder values, stakeholder-ES relationships, and resource management networks. Through our approach, we address a key gap in the literature regarding the operationalization of ES governance, by seeing ES governance as a 'relational network' of multiple different stakeholders, relationships and ES.

4.1. *Broadscale assessment of ecosystem service co-production relationships: From governance to valuation*

It is widely acknowledged that ES are coproduced by the interactions between ecosystems and people, and that stakeholders in a particular landscape can be both beneficiaries and/or co-producers of ES (Spangenberg et al. 2014, Biggs et al. 2015, IPBES 2019). Thus, although many studies have focused on farmers as key actors which modify ES through their direct interactions with landscapes (Förster et al. 2015, Lienhoop and Schröter-Schlaack 2018, Mason et al. 2020), we are in need of approaches which capture the fuller complexity of stakeholder-ES relationships (but see Jericó-Daminello et al. 2021). Our study fills this literature gap by mapping relationships beyond direct modification of ES provision, but also indirect modification through development of collective action, development or implementation of legislation and policy, or gathering and spreading of knowledge and information (Alonso Roldán et al. 2015, Barnaud et al. 2018). By systematically mapping the relationships between different stakeholders and ES, our results reveal the diversity of groups involved in ES governance and management, which range from farmers producing food to local associations who organize around natural and cultural heritage preservation and access. Understanding the full web of relationships between actors and ES is key for understanding entry points and levers for ES management interventions, or the effect that landscape planning and ES intervention measures have on ES benefits (Rozas-Vásquez et al. 2019). This broadscale look is important since uptake of the ES concept into management and practitioner environments is still slow (Grêt-Regamey et al. 2017, Brown et al. 2020, Chan and Satterfield 2020, Longato et al. 2021). Our study explicitly considers the research attention received by different ES as a key aspect of their co-production, since the role of knowledge and information in the management of landscape benefits is well established (Opdam et al. 2016) but has not been considered important in ES before (Longato et al. 2021). This allowed us to show that some highly valued or managed ES in NBR, such as energy production and supply, receive little research attention, which highlights a potential gap for evidence-based management and continued supply of these under-researched ES. Despite being within the primary energy producing region in Norway, we found a significant gap in research on energy production as an ES. Considering energy was also one of the ES least valued by stakeholders, our results suggest the need for further investigation into the effects of proposed and ongoing hydro- and wind-power developments on the landscape and its associated values.

Although social and policy research in ES is expanding (Chan and Satterfield 2020) there are still significant gaps in our understanding of the social components of the ES cascade (Spangenberg et al. 2014); for example, the role of different stakeholders in collective action for ES or the need to consider heterogenous stakeholder groups with diverse interests (Barnaud et al. 2018, Vialatte et al. 2019). ES bundles have become one way of evaluating ES provision diversity, ES co-occurrence and stakeholder values (Raudsepp-Hearne et al. 2010, Malmborg et al. 2021,Cusens et al. 2022), but in this work we use them for the first time to map stakeholder-ES relationships and which stakeholders are relevant to the provision of each ES (but see Jericó-Daminello et al. 2021). Our stakeholder-ES relationship bundles allowed us to examine multiple social elements of ES production, from the ES benefits received by inhabitants in our study region to how these are being directly managed, legislated, and studied and by whom. Although some of our results are unsurprising, for example confirming the important role of farmers in the supply of provisioning ES, we also show that some ES types, like cultural ES, are influenced and co-produced by a more diverse set of stakeholders. For example, community clubs and groups ("*lag og foreiningar*") who organize to improve access to cultural ES and enhance the benefits of these ES for local communities. Our work also confirms that farmers (which were highly represented in our survey) see themselves as important co-producers or stewards of cultural ES which provide benefits to wider society within the region (Kvakkestad et al. 2015). Interestingly however, farmers did not often see themselves as co-producers of other ES like climate change mitigation or protection from extreme weather events, a surprising result given the importance of agricultural practices for climate change mitigation, and the impacts that climate change may have on farmers' livelihoods. These results highlight the importance of understanding key stakeholders' mental models of social-ecological inter-dependence, and how they view the effects of their activities on the landscapes and ecosystems they modify (Mathevet et al. 2011, Barnaud et al. 2018).

4.2. *Disentangling governance of cultural, provisioning, supporting and regulating services*

By constructing social networks for each broad ES category across a multifunctional landscape, our results are a novel contribution showing clear differences in broad-scale organization of ES governance and management, with distinct levels of stakeholder participation, and social network centralization, connectedness, and structure. Past ES governance research has often focused on the governance networks ensuring the provision of specific services, such as carbon offsetting (Buckley

Biggs et al., 2021), particularly in the context of market-based policy tools like Payment for Ecosystem services (PES) (Cook et al. 2016, Meyer et al. 2018, Schröter et al. 2018). Our work is distinct in that it explicitly maps the complex multi-actor co-production networks involved in multiple ES governance, a useful tool for approaching the complexity of interactions and interdependencies between ES, the high amount of stakeholder collaboration required in their management, and the limitations and risks of single-ES or single-stakeholder approaches to ES interventions (Loft et al. 2015, Berbés-Blázquez et al. 2016, Lienhoop and Schröter-Schlaack 2018).

One of the key findings of our study are the structural differences between co-production networks involved in the co-production of cultural, provisioning, and regulating and maintenance ES. The cultural ES network was the most sparce of our analysed networks, with the least number of connections between different stakeholder groups. Some of the main stewards of cultural ES revealed through the stakeholder ES bundles (e.g., landowners, farmers, hunters and fishers), were not so well connected to the co-production network, whereas some, like local community groups and local government bodies were well connected. The mismatch or asymmetry between the level of involvement in on-the-ground management, and importance in the governance network, was reflected throughout the cultural ES governance and management clusters (or "cliques"), which did not cross spatial or institutional scales, but were rather reflective of level of connectedness and sector. Given that cultural ES were the most highly valued by NBR stakeholders, our findings point to a weakness in cultural ES governance and the need of incorporating cultural ES more clearly into natural resource management and collaboration agendas. In addition, our study shows a need for higher involvement of all relevant stakeholders in the planning and consultation of cultural ES development in the region, in particular farmers, given their extensive role in maintaining the cultural landscape in Norway (Kvakkestad et al. 2015). Involvement of key stakeholders in the cultural ES governance and management network would also be key for the provision of outdoor recreation, which was the most valued ES by the local community in this study. This is particularly relevant in the Norwegian context, which is well known for *allemannsretten* ('freedom to roam'), meaning local landowners could be key to the provision of outdoor recreation. Given the importance of cultural ES across European landscapes (Fagerholm et al. 2019), it is important to consider the development of cultural ES governance and management networks which include all relevant players across scales, and account for power inequalities and influence in decision making (Berbés-Blázquez et al. 2016, Barnaud et al. 2018), specifically in the context of BRs or Protected Areas (Barraclough et al. 2021b, Barraclough et al., 2021a).

We show that the regulating and maintenance ES governance and management network was one of the least concentrated. This was reflected both in the lack of centralization in the social network and in the stakeholder ES bundles, which showed regulating and maintenance ES evenly spread out across a high diversity of stakeholders (which included farmers and fishers, industry, local, regional and national government, scientists and researchers, and organizations). As opposed to cultural ES, stakeholder centrality and other social network measures of the regulating and maintenance ES matched well with the level of connection to this ES, i.e., not involved, not well connected. Social cliques also crossed different levels of involvement, in addition to different spatial and governance scales, for example, with farmers and research organizations closely connected in the same cliques. Our results thus could be indicative of a polycentric governance system which is well suited to the management of regulating and maintenance ES, a public good that is decentralized by nature (Muradian and Rival 2012, Falk et al. 2018). However, our work did identify a potential weakness when it came to climate change mitigation potential in NBR which showed different trends to other regulating ES like clean air, water, and soil. We found a distinct gap in management and governance connections to climate change mitigation and extreme weather event protection, with key stakeholders (like farmers and landowners) not considering themselves as co-producers of this ES. These results confirm the difficulties of governing ES when the ES providers and/or beneficiaries operate at distant scales and locations, and when the scale of the ecological processes is so mismatched with the scale of management, resulting in social-ecological misfit (Gómez-Baggethun et al. 2013).

The provisioning ES network was the most centralized with farmers and local governments as the most connected actors, and most like the general natural resource management network. In contrast to the other ES networks, cliques seemed to represent the three sectors of either knowledge, governance, or production. Our results demonstrate that simply mapping natural resource management networks, as has been done abundantly in the literature (Groce et al. 2019, Mason et al. 2020), might not be enough to disentangle and understand the networks governing ES, in particular for regulating and maintenance or cultural ES. By mapping each ES stakeholder network distinctly, our results provide an empirical investigation into the theories proposing that ES are a broad umbrella encompassing different kinds of goods, both public and common, which should be approached through a variety of governance strategies that cross institutional and spatial scales (Muradian and Rival 2012). Our work also confirms that, in addition to understanding the structure of natural resource management networks, it is important to gain an improved understanding of *what* is being discussed and by *whom*, and if interactions in those networks are considered positive or negative (Bodin et al. 2019, 2020).

4.3. Polycentricity, collaboration and diversity in an integrated approach to ecosystem service co-production

Providing a broadscale social-ecological systems' understanding of the social-ecological landscape of ES governance and management in NBR, our work constitutes an empirical approach to combining frameworks developed around collective action theory and the ES framework (Ostrom 2009, Haines-Young and Potschin 2010, Partelow and Winkler 2016, Barnaud et al. 2018, Primmer et al. 2021). As a method suitable to approach social-ecological system's complexity (Preiser et al. 2018), social network analysis has been applied extensively in natural resource management contexts in general (Bodin et al. 2019, Groce et al. 2019). However, the use of tools like social network analysis is still novel in the field of ES governance (Sattler et al. 2018, Schröter et al. 2018, Mason et al. 2020). We expand on existing work by showing that, due to the diversity of ES (both as common, public or private goods, or as processes which function at different scales), each ES class is embedded within structurally distinct co-production networks. One example of this is how we showed distinct levels of centralization, stakeholder participation, and cross-scale/cross-sector connections in each of the ES governance and management networks and community clusters. There were many cross-sector and cross-scale connections in the network cliques for the regulating and maintenance ES network, which were not present in either the provisioning or the cultural ES networks. The existence of cross-scale connections in ES governance networks are important, since they allow for the flow of different kinds of knowledge and information essential to ES management, and can help in processes of social-ecological learning through sharing of experience and perspectives (Olsson et al. 2004). Thus, we show our method could be a useful diagnostic tool to understand collaboration and diversity in ES management, and our work constitutes an empirical investigation into resilience theories of polycentric governance for ES, and social-ecological network diversity and connectivity, which are still notably scarce in the literature (Galaz et al., 2012).

In addition, our social network analysis shows the decentralization of environmental governance in Norway, which has recently been implemented (Kristine and Lundberg 2014, Hongslo et al. 2016), as seen by the strong degree centrality of local municipalities in our analysed networks. Decentralization is considered an example of polycentricity often considered to be positive, as it increases the fit between institutions and local environmental issues (Biggs et al. 2015, Cook et al.

2016). However, it can also be considered problematic when decisions at local scales do not account for large scale trends. Bridging institutions could help coordinate larger scale action for certain ES benefits, for example in the case of our study, cultural ES. Our results point to the potential role of the Biosphere Reserve group as a bridging organization for cultural ES, since it showed the highest score for betweenness centrality, a measure of brokerage (Guerrero et al. 2018). Due to the flexibility and diversity in BR implementation, BRs have been documented to function as bridging organizations which can encourage dialogue and collaboration for ES across multiple stakeholder groups (Förster et al. 2015, Schultz et al. 2018). Thus, BRs could be a good example of overlapping multi-layered governance arrangements for ES (Gómez-Baggethun et al. 2013, Cook et al. 2016).

5. Conclusions

Our study helps fill the lack of empirical work developing the social components of ES on a regional scale. Our systematic analysis of stakeholder networks involved in the governance, management and study of different ES helps understand the alignment between ES governance and social-cultural values for ES in the study region. Ecosystem services bundles have been shown to be an easy way to assess ES multifunctionality in a landscape (Malmborg et al. 2021), and we propose they are also a useful tool to understand diversity of ES co-production and stakeholder roles in a landscape (Jericó-Daminello et al. 2021). Combining these with social network analysis provides a large-scale view of ES governance, and potential mismatches between stakeholder interests across a large landscape. Further work should explore the potential of these methods to pinpoint conflict potential between ES users and the governance network, due to conflicting values, different priorities and ES trade-offs. Further work should also investigate why stakeholders identify themselves as holding specific roles in ES governance, a topic which we have only superficially addressed by creating *a priori* categories (Jericó-Daminello et al. 2021).

In addition to methodological advances, our results also reveal some of the key challenges underlying ES management. The different nature of ES as, for example, commons or public goods, which are connected in different ways to the established natural resource management institutional and traditional structures, means ES management networks are not always fitted to a specific ES – a form of scale mismatch. We propose that studies on ES governance and management need tailored approaches which consider the nature of each good and the level of centralization of its management. Our example points towards a potential “weakness” for cultural ES management. Firstly, cultural ES were not always explicitly considered by those connected to natural resource management. Secondly, the social network communicating about cultural ES management was the least well-connected social network, with key “ES caretakers” like farmers and hunters, not strongly connected to other actors in the network. This could be the source of conflict, considering the extensive role of farmers in the maintaining cultural landscape and recreational pathways in outfield areas in Norway (Bernués, Clemetsen, & Eik, 2016; Bernués, Rodríguez-Ortega, Alfnes, Clemetsen, & Eik, 2015; Kvakkestad, Rørstad, & Vatn, 2015).

We highlight the potential role of bridging organizations to help increase social-ecological fit of ES governance and management networks, such as the capacity of the BR organization to be a bridging organization for cultural ES management found in our work. Our study reinstates the importance of considering multi-level network approaches to ES governance and management. We propose the notion of *ES stewardship* as a concept which more accurately encompasses the multi-level and multi-actor ES co-production that occurs across multifunctional landscapes.

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

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101461.

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Supplementary Material: Mapping stakeholder networks for the co-production of multiple ecosystem services: a novel mixed-methods approach

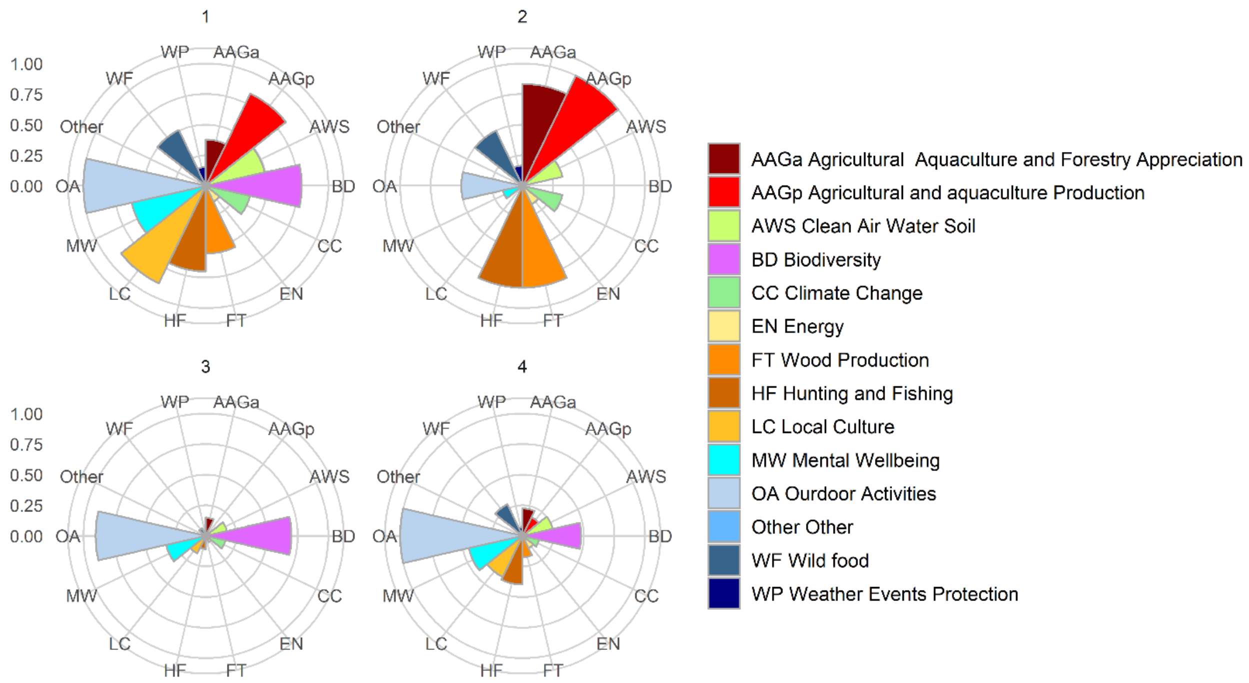

Figure 1: Bundles of stakeholder valuation of ES obtained through a participatory mapping PPGIS survey. Bundles represent stakeholders grouped by similarity of ES valuation, and flowers represent average scores for each ES calculated by summing placed points and scaling them between 0 and 1.

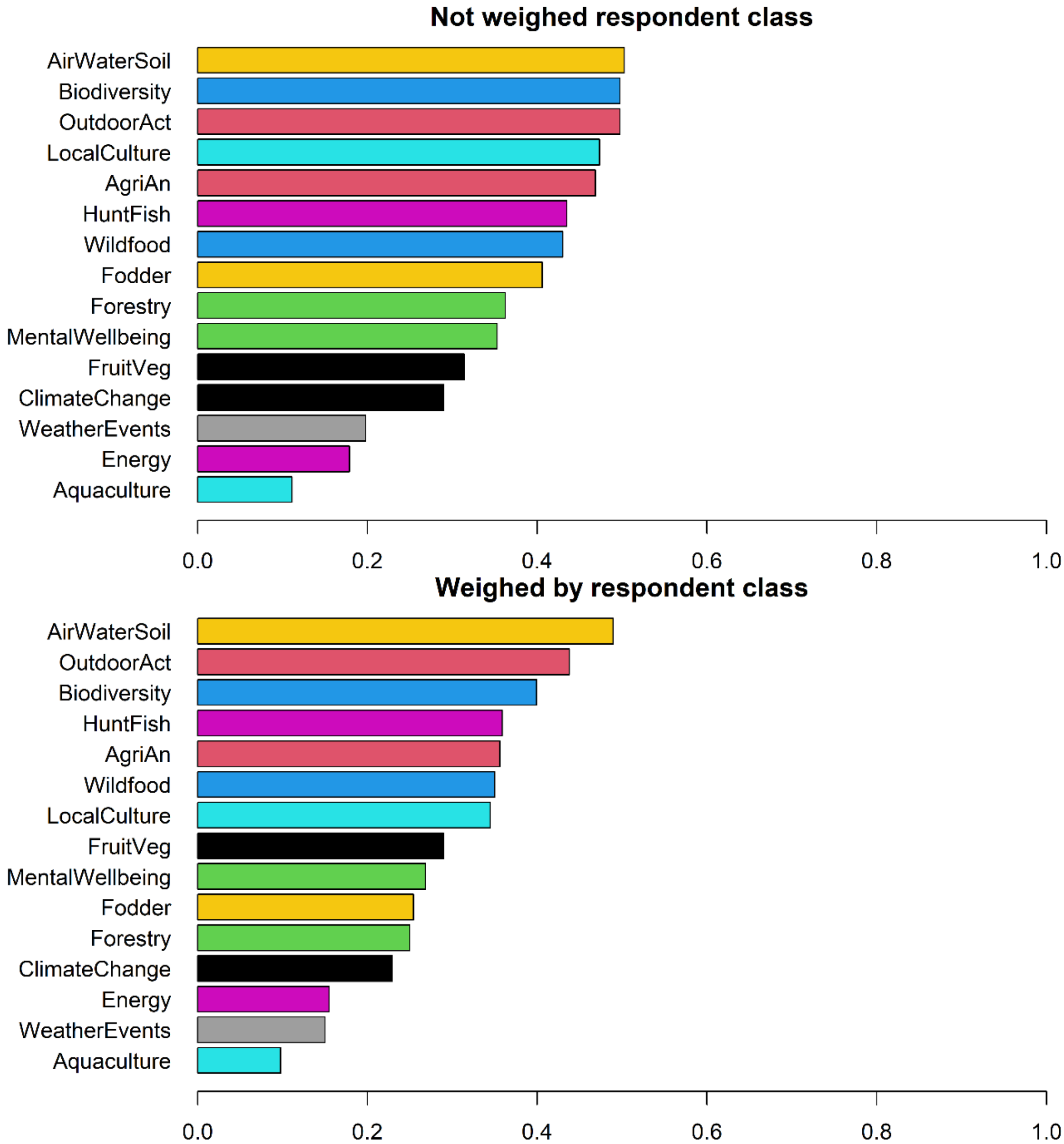

Figure 2: Methodology regarding weighting relationships between stakeholders and ES. Here we present results calculated by two methods, either weighed by respondent type versus non weighed. We decided the most correct version is weighed by respondents because it gives an idea of the average of each group's connection to ES, independent to how many of each respondent class contributed to the survey (and thus correcting for sampling bias). The only ranking that changes significantly is Local culture that drops from 4^{th} to 7^{th} position. Farmers were some of the most numerous respondents, so it makes sense than when we correct for their numbers Local culture goes down in importance. The top three are always water, air and soil, outdoor activities and biodiversity. Animal agriculture is always fifth, and hunting and fishing is either in 4^{th} or 6^{th} position. Climate change, energy and weather events are always towards the bottom of the scale.

Figure 3: Result from the clustering analysis of ES governance relationships, clustering stakeholders by similarity.

Table 1 Social Network participants – here we show the number of participants used to make the social network calculations, since not all survey participants survey responses (main document Table 1) were deemed valid and thus were not included in the network analysis

BR	1
Farmers	51
Hunters	12
Industry	14
Local	17
National	2
Organizations	11
Regional	3
Research	10
Local clubs	8

Additional Material:

The full content of the survey can be accessed here: https://app.maptionnaire.com/en/6998/

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