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Ecosystem service supply and (in)equality archetypes

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ABSTRACT

Overall patterns of ecosystem services (ES) supplied by a landscape often hide distributional (in)equalities that condition how the benefits from nature are provided and used by people. This is evident in landscapes dominated by private ownership and composed of a mosaic of property sizes, across which ES supply can vary substantially. So far, the distributional inequalities in ES supply have been assessed only implicitly through the identification of ES bundles that yield hotspots and coldspots, whereas explicit analyses of how ES supply is shaped by distributional (in)equalities are lacking. Taking southern Chile as a case study, we applied a clustering approach at the municipality scale ($n = 177$), using data at the property level to identify archetypes in (i) the supply of eight ES and (ii) the (in)equalities of that supply using the Gini coefficient. We then analyzed the spatial co-occurrence between ES supply and (in)equality archetypes, to identify which patterns of (in)equality intersect with the supply of ES. We obtained six ES supply archetypes and ten (in)equality archetypes that showed characteristic spatial patterns. Supply archetypes were spatially dominated by a single archetype, which had below average values in the supply of all ES. Contrarily, (in)equality archetypes presented a more heterogeneous distribution across the study area. ES supply archetypes were defined by regulating and cultural ES, whereas (in)equality archetypes were shaped by provisioning and regulating ES. Spatial co-occurrence analysis showed that the dominant ES supply archetype encompassed all (in)equality archetypes – suggesting that property structure can modulate the (in)equality at which ES are supplied. We discuss the policy and management implications arising from the different co-occurring levels of ES supply and (in)equalities. Understanding the linkages between ES supply and distributional (in)equalities at large spatial scales and high resolution can help to prioritize spatial interventions seeking to improve equitable and sustainable ES supply.

1. Introduction

(In)equality is one of the pivotal social challenges of our epoch, with far-reaching implications for human wellbeing (Hamann et al., 2018). In the environmental realm, (in)equality issues have been gaining importance in academic, political, and societal discourses (Burch et al., 2019; Hamann et al., 2018; Klinsky et al., 2017), and currently are recognized to be closely linked to the main environmental problems of our time such as the biodiversity crisis and climate change. Indeed, (in)equality issues are increasingly being discussed at international venues, and feature prominently in major international conventions such as the Sustainable Development Goals (SDGs), the Intergovernmental Panel for

Biodiversity and Ecosystem Services (IPBES), and the Convention of Biological Diversity (CBD) (IPBES, 2019; United Nations, 2016; United Nations, 1992). Equality is an egalitarian ideal, often in the context of distribution (Syme, 2018). In turn, inequality refers to a lack of evenness in the distribution of goods and services across society, so when there is inequality, divisions exist that favor or create opportunities for only a portion of society (Schuppert and Wallimann-Helmer, 2015). Inequality often results from unfair procedural and distributive systems (Burch et al., 2019; Deutz, 2014), and infiltrates many domains of social life, including income, gender, education, environmental risks, or the access to natural capital and ecosystem services (Ragin and Fiss, 2017).

Ecosystem services (ES) or nature's contributions to people are the

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benefits that humans gain from ecosystems and that contribute to their wellbeing (Díaz et al., 2018) – but neither are the benefits always used or accessed in an equitable manner by all individuals of a society, nor are the services supplied equitably across territories. For example, within a landscape, high total levels of ES (e.g., native timber or carbon storage) can be supplied but they can be unequally distributed across rural properties (i.e., some properties provide a lot more per unit of area than others). Alternatively, low total levels of ES can be supplied but they can be equally distributed (i.e., all properties supply similar amounts).

ES research is therefore challenged to investigate how (in)equalities arise and how they are embedded in complex and ever-changing social-ecological systems facing competing economic and political pressures to allocate limited resources and ES that will eventually affect wellbeing (Burch et al., 2019; Ehresman and Okereke, 2015). Here, we refer to (in) equality as “spatial distributive (in)equality”, which is one dimension of (in)equality (Ragin and Fiss, 2017), and the most frequently used in ES studies (Benra and Nahuelhual, 2019). Spatial distributive (in)equalities often relate to issues of distribution of land and resource ownership which are often the cause, mechanism and effect of unjust social-ecological systems (Nahuelhual et al., 2019; Wilkinson and Pickett, 2009). Conversely, the similar concept of spatial distributive (in)equities deals with a variety of socio-economic aspects and the traditional equity dimensions on top of the raw distributional (in)equalities (McDermott et al 2013; Atkinson and Ovando, 2021). In this work we focus on inequality rather than inequity.

The spatial distributive (in)equality of the supply of ES has two dimensions: (i) distribution of access, that is, the (un)equal capacity of direct and indirect beneficiaries to access and capture the benefits derived from the environment (Dade et al., 2022; Ribot and Peluso, 2003); and (ii) distribution of supply, that is, the (un)equal capacity of the environment to provide ES (Atkinson and Ovando, 2021). Both dimensions can be interrelated, because the likelihood of accessing some ecosystem services is higher in locations where that service is readily supplied; notably, other ecosystem services such as carbon sequestration are globally available to possible beneficiaries, no matter where they are being generated. Overall, the (in)equality of the supply, access, and governance of ES can create (in)equity, deprivation, and lead to social-ecological traps where poverty and social conflicts may feedback into environmental degradation or conservation conflicts (Boonstra et al., 2016; Boyce et al., 2016; Leach, 2016). For example, unequal land distribution can reduce chances to provide some ES for more marginalized groups, decreasing their economic possibilities and possibly causing a poverty trap (Boonstra et al, 2016; Nahuelhual et al 2019). To date, access has received a lot of attention in (in)equality and (in)equity discourses – it relates to the distributive (in)equality of “who gets to benefit from what” (Dade et al., 2022; Schultner et al., 2021). For instance, Dade et al., (2022) analyzed different property regimes in a New York state protected area in relation to their ability to be “accessed” by different stakeholder groups. Questions around access directly arise from the seminal works of Ribot and Peluso (2003) and Schlager and Ostrom (1992), who focused on access as the ability to derive natural resources from a property based on social relationships and structures, arising from different bundles of rights held by different people.

Conversely, fewer studies have focused on distributional (in)equalities in the supply of ES as an intersection between the biophysical provision of ES and property boundaries. Such (in)equalities exist inherently in nature, but human interventions can exacerbate them (Adamopoulos, 2008). This is especially the case in regimes of private land ownership, where the supply of ES depends on the capacity and decisions of many individual suppliers (e.g., landowners) with different contextual and enabling conditions related to, among others, the biophysical environment (e.g., quality of land), property size and socio-economic factors and co-production capacity (Atkinson and Ovando, 2021; Kachler et al., 2023). In such contexts, it is important to unpack who supplies what, especially when environmental policies like payments for ES are considered, so that incentives for ES supply are just, and

reflect social-ecological realities on the ground. However, environmental decisions have rarely relied on detailed knowledge of ES supply data across properties and spatial scales (De Lima et al., 2017; Ferraro et al., 2015; Liu et al., 2022).

ES supply is important to people at different scales, and the varied nature of ES supply and spatial (in)equalities in different landscapes poses a challenge to exploring the potential effects of their interactions and how it can affect people’s wellbeing. So far, the distributional inequalities in ES supply have been assessed only implicitly through the identification of ES bundles that yield hotspots and coldspots of ES supply (Benra and Nahuelhual, 2019; Ramirez-Gomez et al., 2020), whereas explicit analyses of how ES supply is shaped by distributional (in)equalities are lacking. Not all locations are equal in terms of their overall supply of ES; major broader scale differences (i.e., large areas with low or high provision of ES) in provision can also intersect with supply differences within smaller administrative units within a region (i.e., a municipality or properties within a municipality).

Therefore, assessing patterns of spatial (in)equalities underlying ES supply across administrative scales (e.g., municipality vs. sub-national) can help identify how both elements relate to each other. Such patterns could be identified by applying an archetype approach, which is being widely used in sustainability science to study the complexity of human-nature interactions from multiple lenses (e.g., governance, land use, vulnerability), although not so commonly in the scope of ES (but see Locatelli et al., 2017). Broadly speaking, archetypes are recurrent patterns of characteristics and processes of a phenomenon of interest that can be observed across cases of study (Oberlack et al., 2019). From a methodological point of view, an archetype approach to ES resonates with the established ES bundle approach (Raudsepp-Hearne et al., 2010; Martín-López et al., 2012; Quintas-Soriano et al., 2019), which has been applied to identify land patches with a homogeneous supply or demand pattern of a set of ES. However, conceptually, the archetype approach provides a more integrative perspective rooted in social-ecological system thinking, which is especially useful to analyze the interactions between diverse social-ecological domains (e.g., ES supply and equality issues) (Eisenack et al., 2021). In this sense, the consideration of the interactions between ES supply and spatial (in)equalities is necessary in the design and implementation of policies related to ES, natural resource management and biodiversity conservation, as well as for policies targeting vulnerable groups of people – issues that have become major challenges of our time (Fisher et al., 2014). Despite rising awareness of the role of (in)equality in understanding the connection between ES and human wellbeing, empirical works that assess such interlinkages remain scarce (Benra et al., 2023).

The overarching goal of this study was to provide an operational framework to analyze how spatial distributional (in)equalities of ES supply shape regional gradients of ES provision. To disentangle how these two dimensions intersect, we used an archetype approach to identify recurrent patterns of ES supply and of (in)equality of ES supply, as well as characteristic co-occurrences between both typologies. This technique has been applied to identify overlaps between land use or social-ecological system archetypes and their changes (Levers et al., 2018; Pacheco-Romero et al., 2021), but not to link the analysis of ES supply and (in)equality patterns in a spatially explicit way. As a case study, we developed a large-scale assessment for eight ES, across seven regions of southern Chile comprising 382,199 private properties and 177 municipalities as our main unit of analysis. Here, we first applied two sets of cluster analysis to identify archetypal patterns of ES supply and supply (in)equalities; and second, we assessed the spatial overlap between ES supply clusters and (in)equality clusters. Our analyses were guided by the following question: *What patterns of spatial (in)equality in the supply of ES intersect with the aggregate supply of ES?*

2. Methods

We developed a dataset of indicators representing the supply of eight

ES and the distributional (in)equality of the supply of those ES. We compiled these indicators for all the municipalities (using data of rural properties) in our study area in southern Chile, and applied cluster analysis to identify and map archetypes of ES supply and of (in)equality of ES supply. Then we overlapped both maps and characterized typical associations between ES supply and (in)equality supply patterns (Fig. 1).

2.1. Study area

The study area comprises seven administrative regions in southern Chile, containing 177 municipalities (Fig. 2). The regions stretch along a north to south axis for 2,380 km and 20 latitude degrees (34.7°S to 55°S), with altitudes ranging from 0 to 4,077 m above sea level. Two mountain ranges – the Andes and the coastal range – and a central valley characterize the study area. In the west, the Andes mountain range spans along the entire study area, acting as a natural barrier for atmospheric flows. The geographic extent and orographic complexity determine the existence of a wide variety of biophysical conditions in the study area. From north to south, the climate regions range from sub-humid and humid Mediterranean, to temperate rain-oceanic, rain-cool oceanic and cold steppe (Kottek et al., 2006). In addition, this regional hydroclimatic conditions are locally shaped by the confluence of the Andes Mountains with the weather fronts coming from the Pacific Ocean (Alvarez-Garreton et al., 2018); for instance, forming “rain shadow” semiarid areas in the east of the Andes Range (in Aysen and Magallanes regions) or hyper-humid areas in the west along the Fjord landscapes, occurring in a matter of a few kilometers (~50–100).

The study area provides for a good case study for two main reasons. First, it comprises an extraordinary diversity of landscapes, with different land uses and degrees of human intervention. Some areas are considered among the last “pristine” territories in the world (e.g., the Fjord landscapes) (Inostroza et al., 2016; Martínez-Harms et al., 2022), and include the majority of Chile’s native forest. These remnant native forests still dominate the Andes Range, and the coastal range in the Los Ríos and Los Lagos regions. Other areas have been highly dynamic in terms of land cover change, with increasing pressures to convert native woodlands, shrubs and pastures to other uses (Nahuelhual et al., 2012; Zamorano-Elgueta et al., 2015). For instance, industrial non-native tree plantations predominate in the coastal range of northern regions, and are expanding to the Andes Range, as well as to the central valley and coastal areas in the Los Ríos and Los Lagos regions. Agricultural production is the most important land use in the central valley, including grain and fruit production, extensive cattle ranching and dairy industry. Second, the properties in the study area are highly unequally distributed (Benra and Nahuelhual, 2019; Jullian and Nahuelhual, 2021). The

properties show an increasing mean size from north to south (Table S2.2) and encompass 382,199 plots. These rural properties (outside officially delineated urban limits) included a majority of private properties which combined farming and forestry plots among others uses, as well as public properties. The dominant land tenure form in Chile is private tenure, hence, for simplicity, we use properties to refer to all tenure forms listed above. Overall, properties located on the mountain ranges are larger, while properties located in the central valley are smaller. Historically, the central valley is the core area for agricultural production but urban–rural migration is causing increased settlement and property subdivision.

2.2. Database development

2.2.1. Ecosystem service indicators

We considered eight ES indicators, namely water supply, water regulation, carbon storage, carbon sequestration, timber supply from native forest, timber supply from non-native tree plantations, recreation opportunities and sediment retention. The main criteria to select these indicators were data availability at the property level and relevance to conservation policies (e.g. protected areas, forest conservation). The total supply for each ES was computed at the property level ($n = 382,199$ property plots or *predios*) using different techniques published in peer-reviewed literature (see indicator metadata in Table 1 and supplementary material 1 for a detailed description of the indicator development). We upscaled the ES indicators obtained at the property level to the municipality level by calculating the average ES supply across plots within each municipality for every ES. In this way we harmonized the ES supply data with (in)equality data, which had to be computed at the municipality level (see section 2.3).

2.2.2. (In)equality of ecosystem service supply indicators

We calculated the Gini coefficient to measure the distributional (in) equality of the supply of the eight ES across the municipalities of the study area. This coefficient has been traditionally applied to analyze (in) equality in the distribution of income, expenditure and wealth (Dorfman, 1979; Solt, 2020), and more recently for measuring environmental (in)equalities such as exposure to industrial pollutants (Boyce et al., 2016; Sun et al., 2010), and ecosystem service distribution in urban (Nyelele and Kroll, 2020) and rural settings (Benra and Nahuelhual, 2019). Here, we use the Gini coefficient to explore inequalities in the supply of ES in the studied municipalities. To calculate the Gini coefficient, we used the following formula (Boyce et al., 2016):

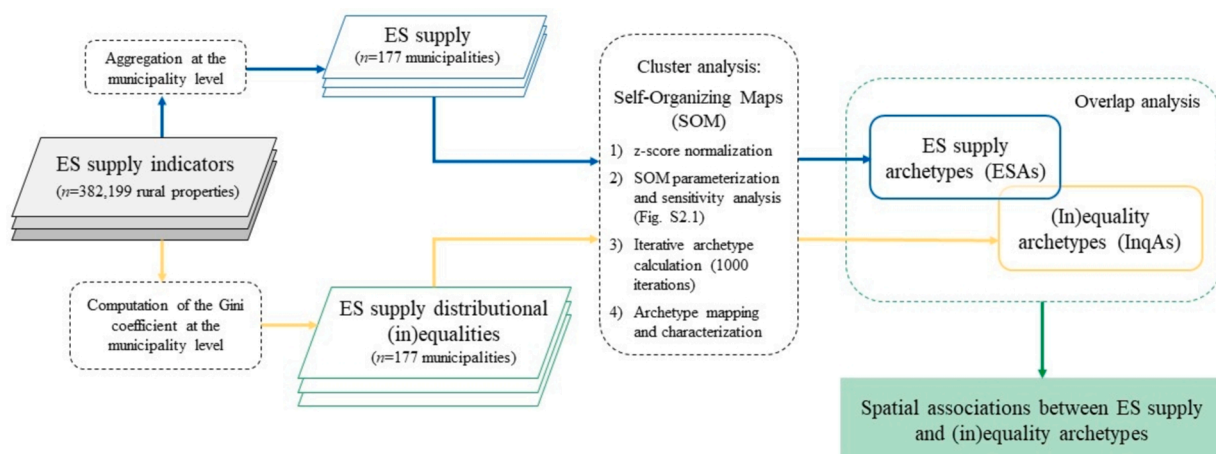


Fig. 1. Operational framework showing a summary of the methodological steps for calculating ES supply and inequality indicators for 177 municipalities using property data.

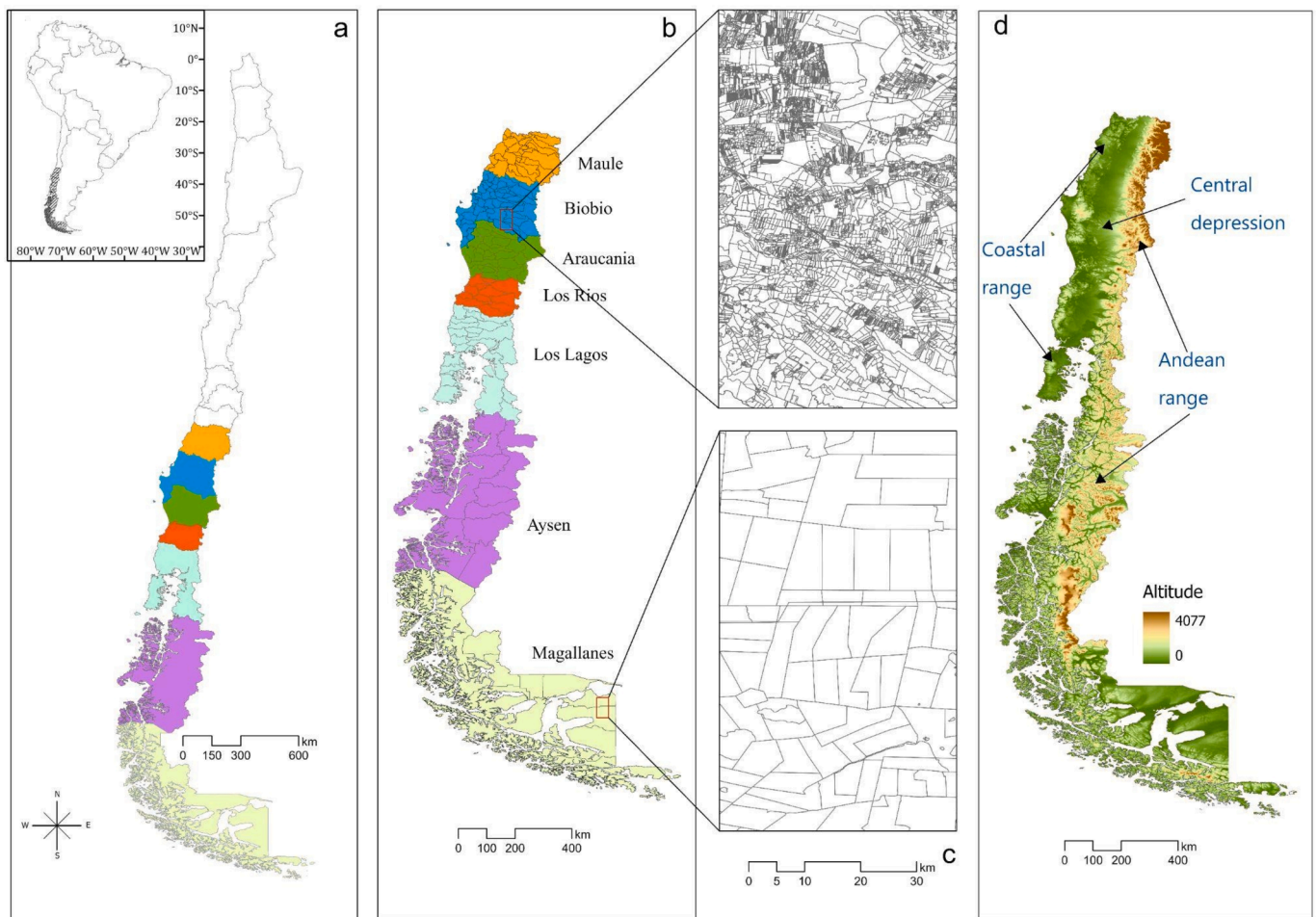


Fig. 2. (a) Study area within Chile, where the inset indicates Chile’s location within the South American continent; (b) the seven administrative regions and its 177 municipalities, where each color represents an administrative region; (c) example of property distribution in two contrasting locations; and (d) elevation. For data availability reasons the recently created Ñuble region (formerly part of Bio-Bio region) was not included in the study.

Table 1
Description and source of the eight ecosystem service indicators.

Ecosystem Service	Category	Description	Unit	Data and references	Software and tool used
Water supply	Provisioning	Portion of total water flow that is fed from deep subsurface and delayed subsurface storage between precipitation and/or snowmelts events (Ward and Robinson, 2000)	m ³ /ha	Benra et al., (2021)	InVEST and R; Seasonal water yield model
Water Regulation	Regulating	Controlled runoff volume after a rainfall event (Guswa et al., 2018)	m ³ /ha	Benra et al., (2021)	InVEST and R; Seasonal water yield model
Timber supply from native forest	Provisioning	Volume of wood from native tree species per hectare	m ³ /ha	INFOR, (2018); https://www.simef.cl	ArcGIS; Geoprocessing tools
Timber supply from non-native tree plantations	Provisioning	Volume of wood from non-native tree species (mainly <i>Eucalyptus</i> spp. and <i>Pinus radiata</i>) per hectare	m ³ /ha	INFOR, (2018); https://www.simef.cl	ArcGIS; Geoprocessing tools
Carbon storage	Regulating	Amount of carbon stored in four carbon pools: aboveground living biomass, belowground living biomass, soil, and dead organic matter	tons/ha	Cabezas et al., (2015; Locher-Krause et al., (2017; Valdés, (2012)	InVEST; Carbon model
Carbon sequestration	Regulating	Net amount of carbon captured/released by living biomass	tons/ha	Cabezas et al., (2015; Locher-Krause et al., (2017; Valdés, (2012)	InVEST; Carbon model
Sediment retention	Regulating	Amount of sediments deposited in water bodies	tons/ha	Benra and Nahuelhual, (2019); Locher-Krause et al., (2017); Nahuelhual et al., (2013)	InVEST and R; Sediment Delivery Ratio model
Recreation potential	Cultural	Potential for recreation activities based on tourism use aptitude, accessibility and scenic beauty	index	Benra and Nahuelhual, (2019); Nahuelhual et al., (2013)	InVEST and ArcGIS; Scenic Quality Model and geoprocessing tools

$$Gini = 1 + \left(\frac{1}{n}\right) - \left[\frac{2}{MEANSUP^2 n^2}\right] \sum_{i=1}^n [(n-i+1) * TOTSUP_i]$$

where TOTSUP_i is total ES supply in each municipality; n = the number of rural properties within the municipality, indexed in non-decreasing order; and MEANSUP is the mean ES supply of all rural properties. The values for this coefficient range between zero and one, with higher values denoting greater inequality. Given the computational logic of the Gini coefficient, that is, the need for a range of values for each ES at the property level within each municipality, the (in)equality of ES supply was obtained at the municipality level. This is the lowest administrative scale in Chile, and also the scale at which decisions are operationalized, particularly with regard to “where”, “how much” and “how (un)equally” ES are supplied, as policy-relevant questions, especially payments for ES (Benra et al., 2022).

2.3. Analysis of ecosystem service supply and (in)equality archetypes

We identified archetypes as recurrent patterns of ES supply and of (in)equality of ES supply across the study area. Each ‘supply archetype’ and ‘(in)equality archetype’ encompassed groups of municipalities with a similar pattern of ES supply, and of (in)equality of ES supply, respectively. To generate these archetypes, we used a cluster analysis methodology by applying the self-organizing maps (SOM) algorithm (package Kohonen, Wehrens and Buydens, 2007; R version 4.2.1, R Development Core Team, 2022) to the datasets on supply and (in)equality indicators. In comparison with traditional cluster techniques such as k-means or hierarchical clustering, SOM clustering depends less on expert knowledge on the study area or on supervised threshold selection to define an adequate number of clusters, and is not restricted by the number of input features (Václavík et al., 2013). We used this method because of its widespread applicability and robustness – it has been used successfully in the field of ES and land use change at a range of spatial scales and with a variety of different spatial data (Václavík et al., 2013; Dittrich et al., 2017; Levers et al., 2018).

First, we standardized the indicators using z-score normalization to obtain zero mean and unit variance. Second, we parameterized the SOM algorithm by defining a priori different numbers of archetypes (from four to 30) and different output grid dimensionalities. Then, we conducted a sensitivity analysis to identify the best possible number of archetypes based on the Davies–Bouldin index (Davies and Bouldin, 1979; Levers et al., 2018) and the mean distance between the z-score indicator values for each municipality and the archetype they belong to (Václavík et al., 2013). For ES supply, the sensitivity analysis revealed an optimal number of six archetypes and a 2x3 dimensionality. For (in)equality we selected ten archetypes and a 5x2 dimensionality (Fig. S2.1a-d). Third, the actual SOM archetypes were calculated iteratively (1000 iterations), and each municipality was assigned to the best matching archetype automatically. Fourth, we mapped archetype memberships for each municipality and characterized the obtained supply and (in)equality archetypes by calculating the average z-score indicator values for the municipalities belonging to the same archetype. We used barplots to visualize how the indicator values in each archetype deviated from the study area average. In addition, we summarized the relative contribution of each ecosystem service category (as defined by CICES; Haines-Young and Potschin, 2013) in each supply and (in)equality archetype. Finally, we investigated which (in)equality archetypes characterized the identified supply archetypes by identifying typical associations through spatial overlap. For the overlap analysis we used ArcGIS Pro version 3.0.0 (ESRI, 2022) and we depicted the results using bubble plots.

3. Results

3.1. Identification and mapping of ecosystem service supply and (in)equality archetypes

We identified six supply archetypes (ESAs) showing characteristic recurrent patterns in the supply of provisioning, cultural and regulating ES across the study area (Table S2.1; Fig. 3; Table S2.3 and S2.5, for reference of archetype name, reference of absolute values in original units and spatial coverage, respectively). Each archetype provided information on: (i) the supply share per ES category within each archetype (percentages next to barplots), and (ii) the supply of each ES regarding the study area average (length and sign of the bars) (Table S2.9). The most widespread archetype was ESA-6 (78.1 % coverage), which mostly supplied regulating ES (53.2 % of the total ES supply) – followed by cultural (34.8 %) and provisioning (12 %) ES – although the supply levels of all ES were below the study area average. In contrast, the rest of the archetypes, although much smaller in terms of spatial extent, showed characteristic contributions to the supply of some ES regarding the study area average. For instance, ESA-4 (2.85 % coverage), encompassing a few scattered municipalities in the northern half of the study area, showed above average supply values for six out of the eight ES assessed across the three ES categories, especially water supply, native timber supply, and water regulation. Within this archetype, the supply of cultural (48.2 %) and regulating ES (38 %) was predominant. In ESA-5 (0.03 % coverage), located in the northern study area, the supply of regulating ES was remarkably dominant, both regarding the study area average and within this archetype. ESA-1 (1.8 % coverage), also encompassing some northern municipalities, had an above average supply of recreation and carbon storage ES, and showed a more balanced supply of the three ES categories. Finally, ESA-2 and especially ESA-3 (9 and 8.2 % of coverage, respectively) were characterized by an above average supply of non-native timber, although in proportion, the supply of provisioning services was considerably lower than the supply of regulating and cultural ES within both archetypes. These ESAs were located mostly in the northern part of the study area in the mountain ranges (Andes and Coastal) and in the central valley, but also included some large municipalities in the south.

We obtained ten (in)equality archetypes (InqA) (Table S2.1; Fig. 4; Table S2.4 and S2.6 for reference of archetype name, reference of absolute values in original units and spatial coverage, respectively). In this case the spatial pattern was more scattered, suggesting a high diversity in the distributional (in)equality levels at which ES are supplied across the municipalities of the study area. Each archetype provided information on: (i) the contribution to inequality per ES category within each (in)equality archetype (percentages next to barplots), and (ii) the (in)equality of the supply of each ES regarding the study area average (length and sign of the bars) (Table S2.10). Overall, regulating services, and in some cases provisioning services, were the most inequitably supplied ES within each archetype. InqA-6 (20 % coverage) showed the highest above average values of distributive inequalities for all ES, especially recreation, carbon sequestration and water supply. Although less remarkable, we also observed above average inequality values for most ES in InqA-1 (1.5 % coverage) and InqA-7 (2.9 % coverage), especially native timber and erosion prevention, respectively. On the contrary, some archetypes generally supplied the majority of ES more “equitably” (i.e., below average inequality values), specially InqA-5 (2.6 % coverage) and InqA-9 (6.7 % coverage), followed by InqA-4 (12.3 % coverage) and InqA-10 (8.4 % coverage). InqA-5 showed more equitable levels of supply of native timber, non-native timber and water regulation, while in InqA-9, the highest equality levels were observed for carbon sequestration, erosion prevention and water supply. The remaining archetypes, InqA-2 (15.1 % coverage), InqA-3 (19 % coverage), and InqA-8 (11.5 % coverage), showed a mixture of above and below average values of distributional (in)equalities. They all similarly showed a more equitable water, carbon storage and recreation

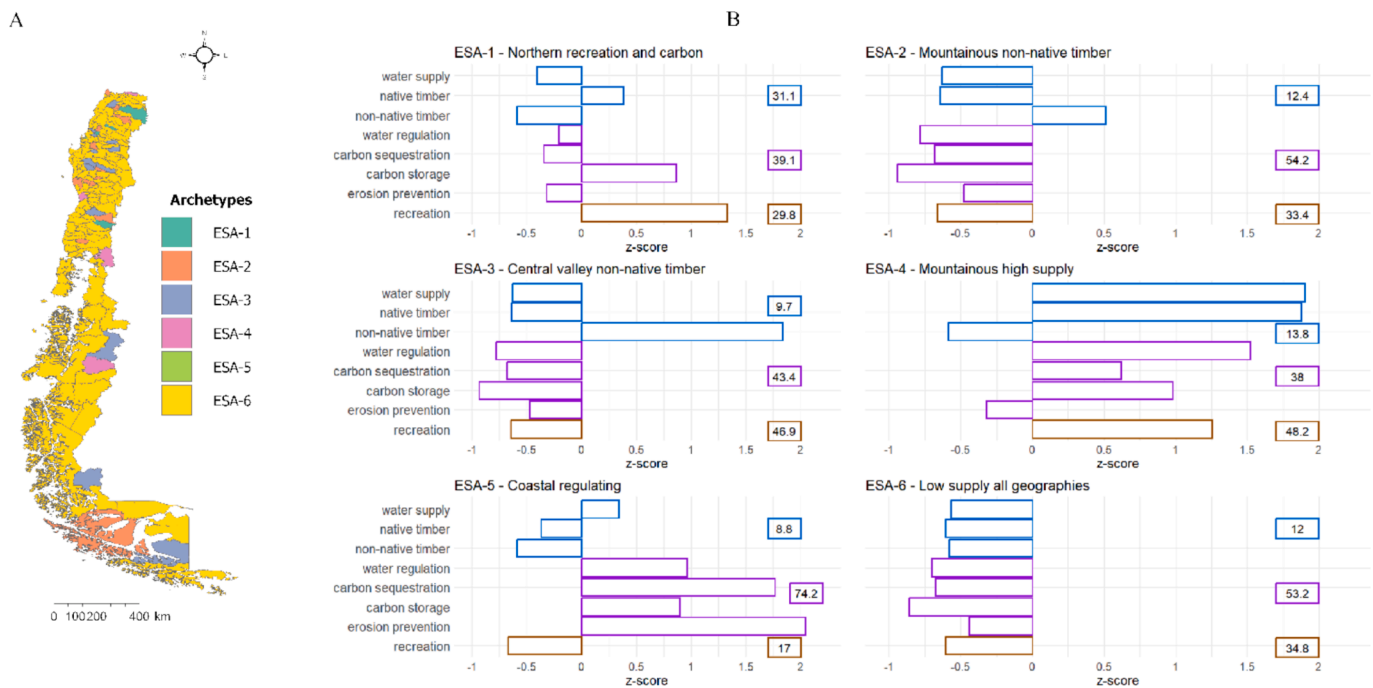


Fig. 3. Ecosystem service archetypes (ESAs) mapped for the study area (panel A). The barplots (codebook vectors; panel B) show the z-score normalized values of ES characterizing each ESA (red: blue, purple: regulating, brown: cultural), with zero representing the study area’s average. The relative contribution of the three categories of ES within each ESA is indicated in percentage next to the barplots. Percentage ratios per ESA area based on the total absolute values of ES indicators (Table S2.3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

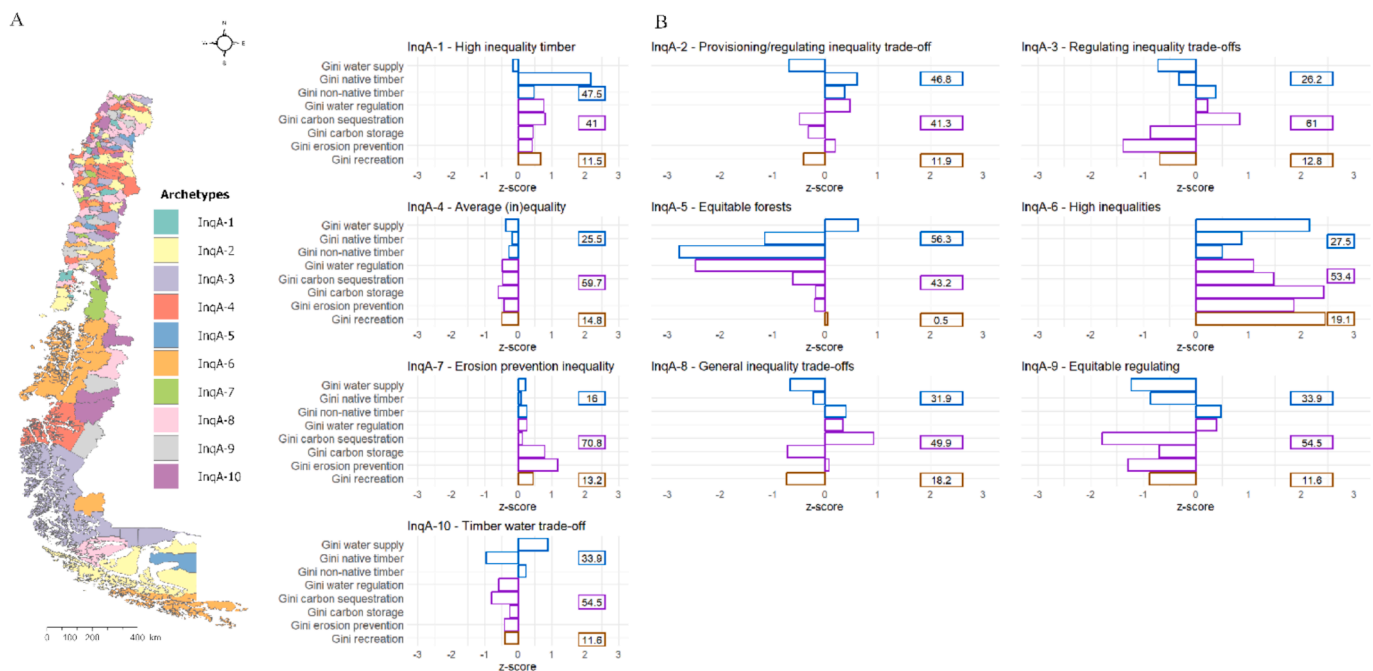


Fig. 4. (In)equality archetypes (InqAs) mapped for the study area (panel A). The barplots (codebook vectors; panel B) show the z-score normalized values of ES characterizing each InqA (blue: provisioning, purple: regulating, brown: cultural), with zero representing the study area’s average. The relative contribution of the three categories of ES within each InqA is indicated in percentage next to the barplots. Percentage ratios per InqA area based on the total absolute values of inequality indicators (Table S2.4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ES supply, and a more inequitable non-native timber supply.

3.2. Spatial associations between ecosystem service supply and (in) equality archetypes

The analysis of the spatial co-occurrence between supply and (in)

equality archetypes identified typical associations between them (Fig. 5). We found that ESA-6, the most widespread archetype, overlapped with all the (in)equality archetypes identified. This co-occurrence revealed that across this apparently homogeneous supply pattern dominating the study area – characterized by a below average supply of all ES – ES were supplied with very diverse (in)equality levels.

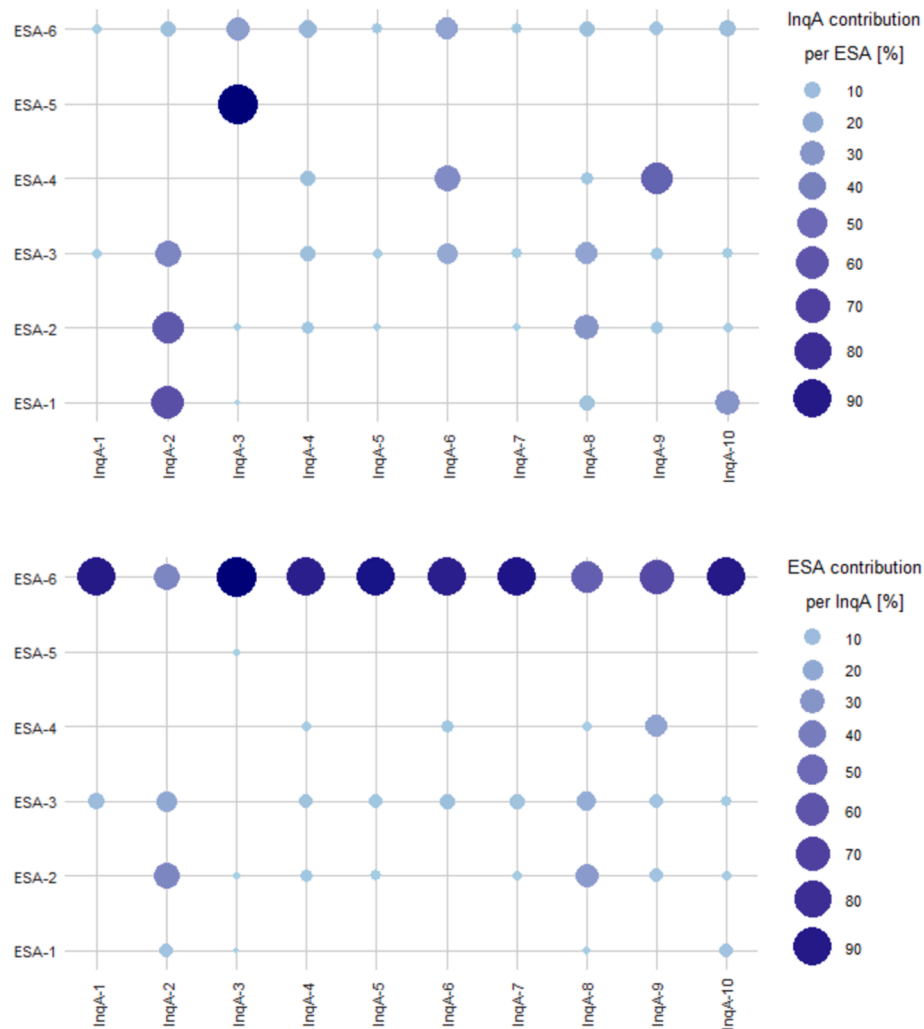


Fig. 5. Spatial coverage (%) of each InqA per ESA (upper panel) and of each ESA per InqA (lower panel). Rows (upper) and columns (lower) sum up to 100% spatial extent. Circle sizes and color gradient depict the magnitude of co-occurrence.

Similarly, ESA-3, characterized by a higher supply of non-native timber, co-occurred with most of the (in)equality archetypes, indicating very diverse (in)equality levels in the supply of ES across this area. From the perspective of the supply archetypes (Fig. 5, upper panel; Table S2.7), typical associations also showed ES supply patterns characterized by more specific (in)equality patterns. This was especially the case for ESA-5, where the dominant supply of regulating ES was more equitable for erosion prevention and carbon storage than for carbon sequestration (InqA-3). In ESA-1, characterized by a higher supply of recreation services and carbon storage, and in ESA-2, with higher non-native timber supply, the overlap with InqA-2 indicated an average (in)equality in the supply of these ES, but not for other relatively minor ES such as water (more equitably supplied) and native timber supply (less equitably supplied). In the case of ESA-4, the overlap with InqA-9 indicated a more equitable supply in one of the highest and most diverse suppliers of ES of the study area. In addition, from the perspective of InqAs (Fig. 5, lower panel; Table S2.8), typical associations revealed that most of the (in)equality archetypes mainly overlapped with ESA6, likely because of the large extent of this supply archetype. Only some (in)equality archetypes showed noteworthy overlaps with multiple supply archetypes, such as InqA-2 and InqA-8 with both ESA-2 and ESA-6, indicating that (in)equality trade-offs within and between service categories mainly affected those ESAs with an overall below average supply of ES.

4. Discussion

Disentangling the complexity of spatial patterns of ES supply is a key challenge for ES research, particularly at the interface of ES supply and the growing field of ES (in)equality. In this study, we provide insights on how different levels of distributional (in)equalities intersect with specific patterns of ES supply. At a regional level, our findings reveal relative homogeneity in ES supply which contrasts with high heterogeneity in distributional (in)equalities. A key insight is that apparent similarity or spatial homogeneity of ES supply can encompass diverse levels of (in)equality. These relationships can be considered when weighing alternative management options for ES associated with particular administrative units or landscapes. Notably, we do not argue that equal supply of ES throughout an entire region is necessarily always better – rather, we argue that in the context of ES management, and especially in the context of payments for ES, a solid understanding of who supplies what is important background information to devise effective and just policy measures. To that end, identifying high-level, archetypal patterns can be a useful first step for assessing how (un)equally ES are provided across larger regions, to then enable more context-specific, regionalized policy making (Dittrich et al., 2017; Goodwin et al., 2022).

4.1. Key insights: Archetype characterization

The characterization and spatial representation of ES supply and distributional (in)equality archetypes in the study area revealed more dominant spatial patterns for ES supply than for (in)equality. Regarding ES supply, two main insights emerged. First, we found that archetypes characterized by below average values comprised the majority of the area and number of municipalities ($n = 140$), indicating substantial spatial homogeneity (Fig. 3). Second, only a few municipalities, mainly located in the northern part of the study area, showed supply values that were above the average of the whole study area. This geographical pattern could be due to the higher net primary productivity and better site conditions of northern regions (Gerding and Schlatter, 1995), which foster the supply of some ES (e.g., native timber, non-native timber, carbon storage). Overall, regulating ES, followed by cultural ES, were dominant in the study area considering the relative proportion of supply within each archetype.

In the case of the (in)equality archetypes, also two main insights emerged. First, a more heterogeneous spatial distribution was observed, compared to the supply patterns, with no dominating archetypes (Fig. 4). This finding suggests that the diversity of property size distribution (Table S2.2), individual landowner decisions, and biophysical conditions, might be influencing the (in)equality with which ES supply is distributed across rural properties and municipalities (Benra and Nahuelhual, 2019; Nahuelhual et al., 2018). For example, two municipalities with a similar ES supply levels but different property size distribution (e.g., municipalities in los Rios Region; Fig. 2), and management inputs might result in the assignment to different (in)equality archetypes, thereby indicating different (in)equality levels shaping such ES supply. Second, the most abundant (in)equality archetype (InqA-6) presented above average inequality for all ES. These areas were located mainly in remote zones in the southern part of the study area which is characterized by vast areas with very large properties and a minor number of clustered smaller properties (Fig. 2). Overall, regulating ES, followed by provisioning ES, contributed the most to the different (in)equality levels in the study area.

4.2. Management and policy implications

Identifying patterns of ES supply and distributional (in)equalities has implications for ES science and policy, and is particularly important for efforts that try to bridge them because addressing inequality is a key national and global policy priority. Chile intends to implement instruments to “maintain, improve and support a sustainable supply of ES” (MMA, 2017), but to date, there is no clear articulation on how to achieve this goal. For example, if we consider payment schemes as a possible instrument: where exactly will these incentives flow to? How will (in)equality issues be included? Which landowners will benefit (Nahuelhual et al 2018)? Our results provide important insights for answering these questions.

The most revealing result was that apparent spatial homogeneity in terms of ES supply can encompass a diversity of (in)equality levels. Inequality in the study area can occur when larger properties concentrate the supply of ES compared to the smaller ones, and equality occurs when smaller properties balance out the supply levels of larger properties (Benra and Nahuelhual, 2019). Another important consideration is that higher or lower (in)equality levels can affect ES that are either dominant or a minority in each archetype (see percentages near barplots in Figs. 3-4), which also has implications for decision making. In practical terms, the results could guide more nuanced and context-specific policies to manage different combinations and trade-offs between different ES supply and (in)equality levels.

For instance, areas with low average ES supply levels and low inequality in their distribution, like the intersection of ESA-6 and InqA-9, could inspect the potential for a landscape level improvement of different ES groups that are currently supplied at low levels (e.g.,

provisioning or regulating). This could be achieved through incentive-based mechanisms like PES schemes or tax reductions, direct regulation policies like forestry sectoral laws, and private–public sector cooperation (Benra et al., 2022; Martínez-Harms et al., 2022; Tecklin and Sepulveda, 2014; Sims, 2023). These areas could focus efforts in increasing efficiency in the supply of ES (if local biophysical conditions allow) as the inequality aspects are not a matter of concern, for example, through watershed restoration for the maintenance of fresh water levels (Lara et al., 2021). This, in turn, could be achieved by transforming grassland or non-native tree plantations on degraded steep slopes into native forest, which would also have a positive effect on biodiversity (Balocchi et al., 2022; Lara et al., 2021). These activities would be in line with calls to diversify ES supply in areas with dominance of non-native timber or degraded grasslands (Little et al., 2021), and would contribute to national restoration commitments in Chile (Bannister et al., 2018; CONAF, 2015).

On the other hand, areas with average low ES supply levels but high inequality in their distribution, like the intersection of ESA-6 with InqA-1 and InqA-2, could focus efforts on more individually improving the supply of certain ES in different property size ranges, gaining additionality and targeting more marginalized landowners (Alarcon et al., 2017). In this way, the low ES supply as well as the inequality levels would be ameliorated. For example, some management actions could include stricter regulations in terms of allowed land uses to avoid more degradation and foster governmental subsidies to restore native forest where timber is especially needed. These actions could guarantee a sustainable supply of ES to nearby communities and should be undertaken respecting local governance (Martínez-Harms et al., 2021; Newig et al., 2023).

Overall, maintaining a balance between sufficient ES supply levels and low inequalities conforms to a great challenge. By linking land protection with the right incentives and mechanisms to local gains, and by zoning and prioritizing the reduction of inequalities in protection goals, this balance can be achieved (Sims, 2023). However, other configurations of ES supply and (in)equality levels in a landscape could be desirable in certain contexts. For instance, rural communities where total ES supply is low and properties are generally small might prefer a more “unequal” ES supply, as they could find difficulties to obtain profitability from incentivizing a more diverse set of ES, due to prevalent “economies of scale”. In this case, incentives might also target the “differentiation” through supporting a more specialized and efficient ES supply by individual properties.

In general, land tenure and property rights are the main drivers of ES supply and (in)equalities in the rural landscapes (Benra et al., 2023; Dade et al., 2022). Two aspects are important here: (i) property size is a structural condition key for ES supply. Therefore, it is harder to tackle by policy, as transformations are slow – like property structure change through selling land – and therefore ES supply changes might not be realized in the short term; and (ii) existing ES supply within properties can be more easily targeted by policy as it partly relies on productive decisions by land managers and therefore changes can be brought about more rapidly. For example, current processes of urban–rural migration and property subdivision in Chile – a change in land tenure configuration – could result in strong changes in quantity and (in)equality of supplied ES. Therefore, ES policy strategies dealing with both aspects will be important in guiding land tenure change and its influence on how ES supply and (in)equalities interact.

4.3. The influence of global processes

Beyond the combination and co-occurrence of ES supply and (in)equalities and management actions derived thereof, two issues emerge from a global perspective that could make both ES supply and (in)equalities change: climate change and telecouplings. In the first case, climate change will strongly impact where and how much ES are supplied as desertification and water scarcity are more prevalent in lower

latitudes in the study area (Alvarez-Garreton et al., 2021). These shifts in the configuration of where and how ES occur can have profound implications in terms of (in)equality, as some landowners might be left with nothing while others might gain productivity. This type of phenomena has been identified in other parts of the world where a lack of ES due to climate calamities forces people to go where ES are still being provided or will be supplied in the future (Adger and Fortnam, 2018; Nicholls et al., 2018; Warner et al., 2010). This, hence, puts extra pressure on areas that are predicted to be suppliers of ES in the future as is the case of Los Rios and Magallanes regions in the study area as opposite to the Mediterranean regions of Maule, BioBio and Araucania. In the second case, telecouplings – the linking of local and regional socioeconomic systems to large-scale global networked socioeconomic and environmental drivers (Liu et al., 2013) – play a fundamental role in how landscapes and landowners' decisions and hence ES supply change over time. Telecouplings can exacerbate inequality in two ways: first, because local people increase dependence on external sources as telecoupled imports, thus, their dependency on local ES is reduced and, second, distant regions producing ES might suffer from an unequal distribution of natural assets and ES (e.g. through land grabbing) or the activities in terms of labor and management that lead to the co-production of ES supply (Benra et al., 2023).

4.4. Advantages, limitations and future research

The data driven clustering approach using SOM provides a non-supervised classification system (Levers et al., 2018; Simensen et al., 2018) that has only been applied in a few cases to identify ES supply archetypes (Dittrich et al., 2017) but not at all in relation to ES supply (in)equality archetypes. This effort to explore recurrent patterns of ES supply and their (in)equalities finds a corollary in the ES disaggregation literature that calls for integrating a plurality of factors such as actors, values, and equality in ES supply assessments (Brück et al., 2022). In this regard, our approach also integrates different spatial scales of analysis: (i) the rural property level, as the smallest available unit of ES supply information, and (ii) the municipality level, at which ES supply data is reaggregated and supply (in)equalities can be calculated. Challenges remain in the availability of updated socio-economic data at the property level, which would have allowed the inclusion of disaggregated analyses including attributes beyond the biophysical ones (Zarbá et al., 2022), and the inclusion of a broader set of ES (e.g. more related to agriculture or cultural ES) and other modeling softwares which would have generated different results.

More generally, the equality considerations in this paper go beyond the mere description of ES supply by providing tools to understand linkages with distributional (in)equality. Revealing such linkages might be a first step to explore (in)equity dimensions such as procedural and recognition aspects (Loos et al., 2023). For example, ES distributional (in)equality can aid in-depth analysis of past and current origins of inequalities, thereby unearthing unjust practices (e.g., formal land distribution processes or not acknowledging equal rights of all people) that should not be repeated. However, these linkages also provide new insights on how to develop operational, fair and just ES policy in the future. We argue that including distributional (in)equality should be a priority of environmental decision-making including in a context of ES. Furthermore, archetype analysis can provide a useful tool for policy communication because it summarizes complex information and patterns into a palatable output. Future research at the interface of ES supply and (in)equalities should provide insights for a diversity of geographical and climatic regions, and land tenure systems, using a variety of biophysical and socio-ecological data at high spatial resolution.

5. Conclusion

This study developed an assessment of eight ES representative of the

diversity of nature's contributions to people's livelihoods and well-being in Chile, and their relation to distributional (in)equalities. We found spatial homogeneity in the supply of ES, but heterogeneity in the (in)equalities with which these ES were supplied by different rural properties. Our analyses also revealed that homogenous supply areas can encompass heterogeneous (in)equality levels, which highlights the influence of land tenure and property size on the (in)equality with which ES are supplied. Hence, integrating different levels of analysis (property and municipality level) is an important first step for addressing challenges posed by inequality issues in rural social-ecological systems. More generally, the distributional equality considerations raised in this paper can lay the foundation to further broaden the scope of ES and (in)equity research by considering other dimensions such as procedural and recognition aspects.

6. Data and code availability

Original data and code are available at https://github.com/benra1990/inequality_archetypes.

CRedit authorship contribution statement

Felipe Benra: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Manuel Pacheco-Romero:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Joern Fischer:** Writing – review & editing, Writing – original draft.

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.

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Appendix A. Supplementary data

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