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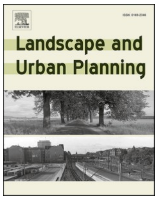

Integrating inductive and deductive analysis to identify and characterize archetypical social-ecological systems and their changes

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HIGHLIGHTS

- Nested archetype analysis to address social-ecological complexity of landscape change.
- Inductive detection of typical social-ecological systems and changes therein.
- Interpretation with deductive types of human-nature connectedness.
- Detection and mapping of key sustainability challenges due to changes in SES.

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ABSTRACT

Archetype analysis is a key tool in landscape and sustainability research to organize social-ecological complexity and to identify social-ecological systems (SESs). While inductive archetype analysis can characterize the diversity of SESs within a region, deductively derived archetypes have greater interpretative power to compare across regions. Here, we developed a novel archetype approach that combines the strengths of both perspectives. We applied inductive clustering to an integrative dataset to map 15 typical SESs for 2016 and 12 social-ecological changes (1999–2016) in Andalusia region (Spain). We linked these types to deductive types of human-nature connectedness, resulting in a nested archetype classification. Our analyses revealed combinations of typical SESs and social-ecological changes that shape them, such as agricultural intensification and *peri*-urbanization in agricultural SESs, declining agriculture in natural SESs or population de-concentration (counter-urbanization) in urban SESs. Likewise, we identified a gradient of human-nature connectedness across SESs and typical social-ecological changes fostering this gradient. This allowed us to map areas that face specific sustainability challenges linked to ongoing regime shifts (e.g., from rural to urbanized systems) and trajectories towards social-ecological traps (e.g., cropland intensification in drylands) associated with decreasing human-nature connectedness. This provides spatial templates for targeting policy responses related to the sustainable intensification of agricultural systems, the disappearance of traditional cropping systems and abandonment of rural lands, or the reconnection of urban population with the local environment, among others. Generally, our approach allows for different levels of abstraction, keeping regional context-specificity while linking to globally recognisable archetypes, and thus to generalization and theory-building efforts.

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1. Introduction

Understanding the interactions between people and nature is at the heart of addressing some of the major sustainability problems we face in the Anthropocene (United Nations, 2015). Analysing such interactions from the perspective of social-ecological systems (SESs) is a promising pathway to foster such understanding (Liu et al., 2007). Sustainability science has made great progresses in constructing theoretical foundations for SES (e.g., Berkes et al., 2003; Chapin et al., 2009; Holling, 2001), as well as in devising conceptual frameworks to operationalize these theories (e.g., Ostrom, 2009). Yet, it remains a major challenge to meaningfully organize the diversity and complexity of social-ecological settings, and the human-nature interactions that characterize them, in order to translate broad theories into practice (Pacheco-Romero et al., 2020; Rocha et al., 2020).

Finding typical, recurring SESs, pathways of change, and their outcomes is a promising avenue in this regard (e.g., Cumming et al., 2014; Fischer-Kowalski et al., 2014; Hamann et al., 2015). Identifying such "archetypes" of SESs and their changes has become an essential tool to reach an intermediate level of abstraction between case specificity and general explanations (Oberlack et al., 2019). Such archetypes reflect recurrent patterns, processes or actors in SESs, and can be derived either inductively (e.g., by identifying common characteristics within a set of case studies), or deductively (e.g., through the theoretical identification of key variables that create a typological space) (Meyfroidt et al., 2018). As a result, archetype analysis has emerged as a central tool in sustainability research to identify major types of human-nature interactions (Oberlack et al., 2019). Because archetypes can be mapped out, such approaches can also be used to target research effort (e.g., by identifying understudied archetypes), thus serving as a basis for contextualized, tailored management and policy making (Sietz et al., 2019). Finally, archetypes allow the synthesis of general patterns, and thus to build middle range theories explaining them (Eisenack et al., 2019; Merton, 1968). Such theories stand between *ad-hoc* descriptions of singular case-studies and universal theories, and provide a pathway towards a more generalized knowledge of social-ecological systems (Meyfroidt et al., 2018).

Inductive and deductive methodologies to identify archetypes of SESs and their changes each have specific advantages (Oberlack et al., 2019). Inductive, data-driven approaches have been essential to generate empirical scientific knowledge on different SES archetypes around the world (Magliocca et al., 2018) and to map SESs at different spatial scales. They allow the identification of SES boundaries, which is crucial to operationalize the SES concept in landscape planning (Carpenter et al., 2009; Martín-López et al., 2017). The main examples include the mapping of anthropogenic biomes (Ellis and Ramankutty, 2008) and land systems (van Asselen & Verburg, 2012; Václavík et al., 2013) at the global scale; or, more regionally, social-ecological functional types (Vallejos et al., 2020), ecosystem service bundles (Hamann et al., 2015; Raudsepp-Hearne et al., 2010), social-ecological hotspots (Alessa et al., 2008), and social-ecological systems (Martín-López et al., 2017; Rocha et al., 2020). A few studies have also extended such static approaches to incorporate temporal dynamics. For instance, Renard et al. (2015) mapped changes in ecosystem services bundles, Levers et al. (2018) mapped archetypical changes of European land systems, or Magliocca et al. (2019) identified archetypical pathways of social and land use change associated with the establishment of economic land concessions. All these studies constitute different ways of representing the convergence between the social and ecological domains (i.e., social-ecological systems), and their comparison would allow to improve the understanding of social-ecological patterns and dynamics across contexts and scales. However, the diverse SES conceptualizations, research questions, and methods used, make it difficult such comparisons (Balvanera, Daw, & et al., 2017), which hampers knowledge generalization and theory building (Magliocca et al., 2018; Meyfroidt et al., 2018).

Deductive approaches can address these shortcomings. Such approaches detect SES archetypes through the theoretical identification of key variables describing human-environment interactions (Meyfroidt et al., 2018). For instance, Fischer-Kowalski et al. (2014) characterized three socio-metabolic regimes (hunter-gatherers, agrarian, and industrial societies) according to human population size, material and energy use, and technology. Cumming et al. (2014) used such an approach to understand the implications of these three regimes for ecosystem services, defining *green-loop*, *transition*, and *red-loop* systems based on the level of connectedness of societies with local ecosystems. Similarly, building on the theory of social-ecological metabolism, Dorninger et al. (2017) defined four archetypes of biophysical human-nature connectedness based on the level of land-use intensification and trade flows. Such deductive archetypes are useful templates to diagnose social-ecological configurations, allowing for comparisons, generalizations, and the transference of insights across regions. However, such archetypes often represent idealized types that can be difficult to find empirically (Oberlack et al., 2019) and may fall short of capturing the full range of situations that exist in the real world (Fischer et al., 2017). Therefore, basing SES characterisations solely on deductive archetype approaches might oversimplify the diversity of social-ecological settings, and this hinder the identification of appropriate, context-tailored policy and governance tools.

Combining inductive and deductive archetype analyses would provide a means to jointly leverage their respective strengths, specifically the power of inductive methods to identify and map SESs in a particular region with the interpretative power of deductive methodologies. In other words, deductive archetypes could be used as diagnostic tool (Braun, 2002) of archetypes identified through empirical work (Dorninger et al., 2017; Oberlack et al., 2019). Integrating both perspectives also allows the incorporation of multiple levels of abstraction (Oberlack et al., 2019). This facilitates knowledge transfer across scales, from local to regional and global contexts (Sietz et al., 2019). A combined approach thus has considerable potential to generalize and contextualize case study observations to inform broader policy dialogues, while still being useful for finding case-specific management responses (Balvanera, Calderón-Contreras, & et al., 2017; Fischer et al., 2017; Magliocca et al., 2018; Václavík et al., 2016).

Despite these advantages, approaches that link inductive and deductive perspectives are scarce. For instance, Hamann et al. (2015) integrated both perspectives by associating three inductively derived bundles of ecosystem service use with *green-loop*, *transition*, and *red-loop* deductive categories of SES dynamics (Cumming et al., 2014). In their work, household-level ecosystem service use (high, medium, and low) was associated with the type and strength of links between people and nature, which allowed the identification of the main sustainability challenges that SESs faced. However, their study used a limited number of SES archetypes (three) and assumed SESs to be static, which is unrealistic. In fact, we know of only one study, by Magliocca et al. (2018), that considered the temporal dimension by identifying archetypical pathways of land-use change due to agricultural expansion, which were then linked to typical configurations of social impacts (e.g., conflicts, migration, displacements). Overall, the integration of top-down (deductive) and bottom-up (inductive) perspectives to identify and study archetypical SESs - and the human-nature interactions that characterize them -is still in its infancy.

Here, our overarching objective was to develop an approach for nested archetype analysis that retains the regional diversity of SESs while allowing for cross-comparison across regions. We aimed to advance the integration of deductive and inductive perspectives for SES archetype analysis in three ways: 1) by adding the temporal dimension; 2) by considering the full diversity of SESs and their changes by means of a data-driven, spatio-temporal identification procedure; and 3) by linking inductively identified SESs into broader deductive categories of human-nature connectedness. As a case study, we chose Andalusia region (Spain), which presents interesting social-ecological gradients. Andalusia is the most populated (ca. 8.4 million inhabitants) and the second largest (ca. 87,200 km^2) region in Spain (Junta de Andalucía, 2019a), with 96% of the population inhabiting urban areas, from big cities to small villages. Andalusia has diverse and well-preserved natural capital, holds the largest protected area network in Spain (>2.8 million ha), and is part of the Mediterranean basin biodiversity hotspot (García Mora et al., 2012; Junta de Andalucía, 2019b). The long presence of humans has shaped landscapes markedly, resulting in tightly connected SESs. However, in the last decades, both land-use intensification and rural abandonment have led to marked changes in natural resources use (García Mora et al., 2012), and thus to changing human-environment interactions. Specifically, we asked the following research questions:

1. What are the typical SESs and the social-ecological changes that have shaped them, as identified by an inductive, spatio-temporal archetype approach?
2. How do these inductive SESs map onto deductive types of human-nature connectedness?

2. Material and methods

We compiled a comprehensive dataset of indicators representing the dimensions of SES functioning across its three main components: social system, ecological system and interactions between them (Liu et al., 2007; Pacheco-Romero et al., 2020; Resilience Alliance, 2007) (Fig. 1). We gathered these indicators for all municipalities in Andalusia for the years 1999 and 2016 and applied cluster analysis to detect and map typical SESs and social-ecological changes (SECHs), and to analyse their spatial overlap. Our second major step assessed how these SESs map onto a set of deductive types (based on Cumming et al., 2014, and Dorninger et al., 2017) that classify SESs according to their human-nature connectedness.

2.1. Database development

We developed a dataset of 26 indicators using open-access regional databases (Table 1). We harmonized all indicators at the municipality level (n = 778 municipalities) for the years 1999 (t_0) and 2016 (t_1), which offered the greatest data availability and a 17-year time span to analyze change. For indicators that were unavailable for t_0 or t_1, we used the closest available date. Our dataset consisted of categorical and continuous indicators, and we aggregated them to the municipality level by calculating the spatial mean for continuous indicators and the relative area share of certain classes for categorical indicators available as raster or shapefile data. As municipalities differ in extent and population, we calculated relative indicator values per unit area or per inhabitant, to ensure comparability among municipalities (Appendix A, Table A.1). To quantify social-ecological change, we calculated absolute differences for all 26 indicators between 1999 and 2016 (cf. Levers et al., 2018). Subsequently, we z-transformed the resulting differences to zero mean and unit standard deviation to make the indicator change comparable. For further description on indicator sources and processing see Appendix A.

2.2. Inductive detection and mapping of typical SESs and social-ecological changes

To classify and map typical social-ecological systems (SESs) in 2016, as well as social-ecological changes (SECHs) between 1999 and 2016, we used hierarchical cluster analysis to group similar municipalities (Fig. 2A). We applied the Manhattan distance and Ward's method to minimize the total variance within clusters (Ward, 1963) using the packages *base*, *stats*, and *graphics* in R (R Core Team, 2018). To determine the optimum number of clusters, we tested different cut-off levels of the cluster dendrogram to obtain a comprehensible picture of the diversity of SESs and SECHs based on our knowledge of the study area. We stopped splitting clusters when any class smaller than 5 municipalities appeared. This yielded a set of 15 typical SESs and 12 SECHs and cluster memberships for each municipality.

To characterize our typical SESs and SECHs, we assessed the magnitude and direction of impact of each indicator for each cluster (cf. Levers et al., 2018). We first averaged indicator values across all municipalities in a specific cluster, and then calculated the deviation (in standard deviations) of the cluster mean to the overall mean of the entire study area. Thus, positive deviances refer to above average values, and negative deviances to below average values, regarding the overall mean for the study area (Appendix A, Table A.2). Based on the impact of indicators in each cluster, our knowledge of the study area, and the literature, we then described, labelled, and classified SESs and SECHs according to their characteristics and spatial patterns. Finally, we overlapped SES and SECH clusters to assess their spatial co-occurrence and to assess which SECHs characterized and potentially led to the SESs in 2016 (cf. Levers et al., 2018).

2.3. Deductive assessment of archetypes

After identifying typical SESs (for 2016) and SECHs (between 1999 and 2016), we assessed and interpreted them in terms of human-nature connectedness (Fig. 2B). Acknowledging that human-nature connectedness is a multifaceted concept that involves external (i.e., material, experiential), and internal connections (i.e., cognitive, emotional, and philosophical), our analysis was only focused on understanding the potential connections in a material and/or experiential sense (Ives et al.,

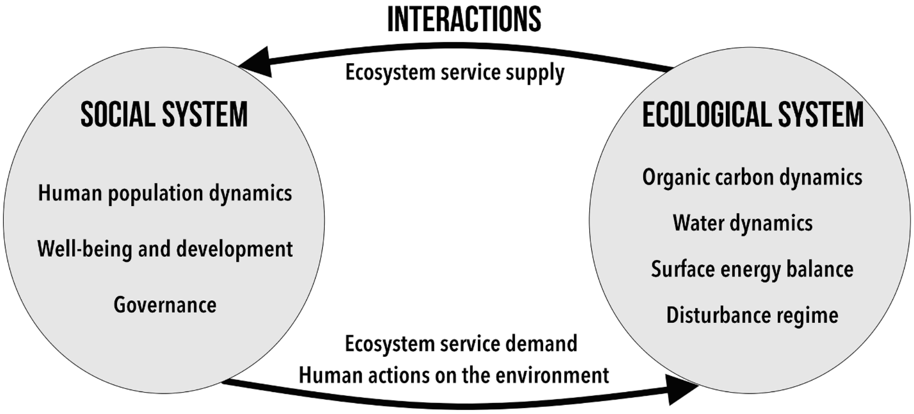

Fig. 1. Conceptual framework of the social-ecological system used to structure the database and to guide the characterization of typical social-ecological systems and social-ecological changes. The three main components of the social-ecological system are shown in capital letters: the social system, the ecological system and the interactions between them. Each component includes the dimensions of social-ecological functioning (modified from Pacheco-Romero et al., 2020).

Table 1
Indicators used for the mapping typical social-ecological systems and their changes. Data sources: Multi-Territorial Information System of Andalusia (SIMA), Institute of Statistics and Cartography of Andalusia (IECA), Environmental Information Network of Andalusia (REDIAM), and Moderate-Resolution Imaging Spectrometer (NASA-MODIS).

Variable	Indicator	Unit	Source
Social system			
Human population dynamics			
Population density	Population density	People km^{-2}	SIMA
Population distribution	Population dispersion	%	SIMA
Population ageing	Population mean age	years	SIMA
Well-being and development			
Employment	Unemployment rate	%	SIMA
Economic level	Mean income	€ contributor^{-1} year^{-1}	SIMA
Governance			
Participation	Turnout in local elections	%	SIMA
Internal capacity of the government	Public expenditure	€ inhabitant^{-1} year^{-1}	SIMA
Ecological System			
Organic carbon dynamics			
Net Primary Productivity (NPP)	Mean annual EVI	Index	NASA-MODIS
Net Primary Productivity seasonality (NPP seasonality)	CV annual EVI	Index	NASA-MODIS
Water dynamics			
Precipitation	Mean annual precipitation	mm year^{-1}	REDIAM
Surface energy balance			
Air temperature	Mean annual temperature	°C	REDIAM
Disturbance regime			
Drought occurrence	Mean drought standardized index	Index	REDIAM
Rainfall torrentiality	Rainfall mean torrentiality	%	REDIAM
Interactions			
Ecosystem service supply			
Cultivated crops (P)	Crop production	Ton ha^{-1} year^{-1}	IECA, SIMA
Reared animals and their outputs (P)	Livestock production (GHG emissions by livestock)	Ton CO$_2$eq ha^{-1} year^{-1}	REDIAM
Global climate regulation by reduction of greenhouse gas concentrations (R)	Carbon sequestration by terrestrial ecosystems	Ton ha^{-1}	REDIAM
Physical and experiential interactions (C)	Landscape diversity index	Index	REDIAM
Ecosystem service demand			
Appropriation of land for agriculture	Cropland area	%	SIMA
Human actions on the environment			
Land use/land cover	Natural surface	%	SIMA
	Artificial surface	%	SIMA
Land use intensity	Cropland productivity	Ton cropland_ha^{-1} year^{-1}	IECA, SIMA
	Irrigated cropland area	% (of total cropland area)	SIMA
Traditional/Organic agriculture	Rainfed crop production	% (of total cropland production)	IECA, SIMA
Transport of goods	CO$_2$ emissions in the transport of goods	Ton CO$_2$eq ha^{-1} year^{-1}	REDIAM
	Total GHG emissions		REDIAM
Anthropogenic greenhouse gases emission		Ton CO$_2$eq ha^{-1} year^{-1}	
Soil erosion	Area with high annual mean erosion	%	SIMA

2017; Ives et al., 2018). Such material and experiential connections arise principally from resource use and the development of recreational activities in contact with nature, respectively (Ives et al., 2018). Specifically, we developed a nested archetype classification that at the first level associated each typical SES to a set of deductive types describing the biophysical connectedness between humans and nature (Dorninger et al., 2017), as an approach to describe material connections. To assess biophysical connectedness, we evaluated three dimensions. The first describes "intraregional connectedness", which comprises the extent to which humans appropriate net primary production. This dimension is used as a baseline for comparison among SESs. The second dimension refers to "biospheric disconnectedness", which relates to the use of materials external to the biosphere (artificial agrochemicals, fossils, machinery, etc.) to increase cropland productivity, and relates to a strong dependence on industrial inputs that displace ecological constraints. Finally, "spatial disconnectedness" relates to the quantity of biomass-based commodities imported to and exported from a SES. This third dimension thus describes the environmental load displacement and the substitution of regionally/locally available biospheric resources by distal ones. We assessed these three dimensions focusing on specific proxies from our database (Appendix A, Table A.3). We compared the magnitude and direction of impact of each proxy (see section 2.2) across SESs. Then, we contrasted the empirical values of our proxies with the relative value of the dimensions according to the conceptual framework of Dorninger et al. (2017) to classify SESs into four deductive types (i.e., *non-industrialized*, *moderately industrialized*, *industrialized export-oriented*, and *industrialized import-dependent*), from high to low biophysical human-nature connectedness (see Fig. 2B). We also used the SECHs to derive the direction and magnitude of change of selected proxies (1999–2016), thereby adding a time dimension to this assessment.

To further assess our identified typical SESs, we established a second, nested level following Cumming et al. (2014) approach, which distinguishes three deductive types (i.e., *green-loop*, *transition*, and *red-loop*), from high to low human-nature connectedness (at least in a material and/or experiential sense) (Fig. 2B). We used the proportion of natural, cropland, and artificial surfaces as proxies of such connectedness. Thus, the dominance of natural and/or cropland surfaces (>50%) was associated with a higher potential material and/or experiential connectedness and therefore to *green-loop* SESs. For instance, we assume that SESs dominated by cropland surfaces are likely to present stronger material connections due to a higher direct consumption and even reliance on locally supplied provisioning ecosystem services (e.g., due to an export-oriented agricultural-based economy). Likewise, those SESs hosting widespread natural areas may also have strong material connections, or at least the opportunity to engage more directly with nature through recreational activities (i.e., experiential connections). Conversely, the dominance of artificial surface (>50%) was associated to a lower connectedness, which characterizes *red-loop* SESs. In this case, urbanization and infrastructure sprawling contribute to distancing people from ecosystems both in a material (i.e., less contact with primary resource base) and experiential sense (i.e., more difficult to reach natural places) (Ives et al., 2018). A balance among natural, cropland, and artificial surfaces (c.a. one third of the total surface for each) was associated to intermediate connectedness, and therefore to *transition* SESs.

Overall, overlapping SESs and SECHs, as well as the characterization of SESs based on the social-ecological states from Cumming et al. (2014) and Dorninger et al. (2017), enabled us to further discuss potential

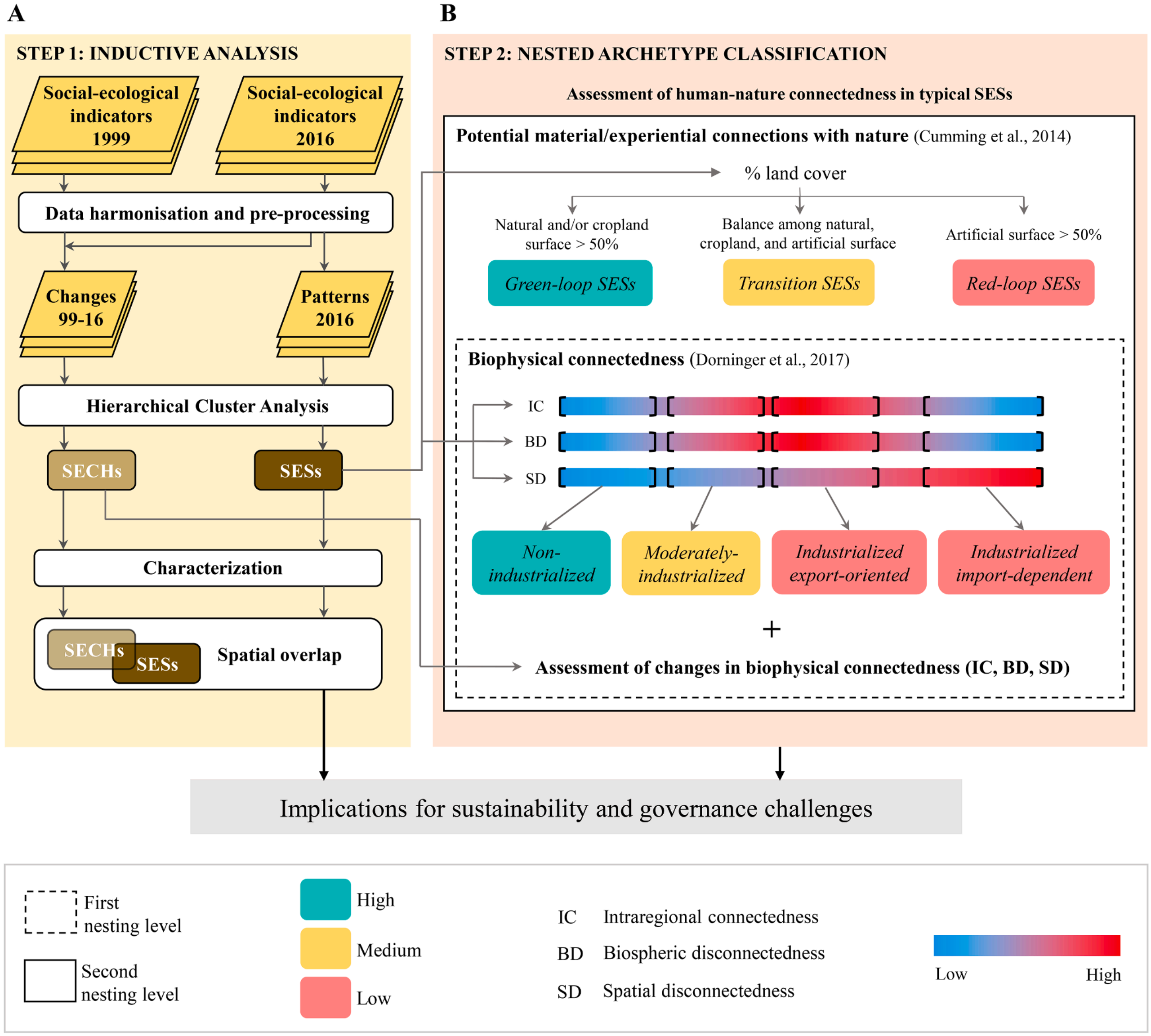

Fig. 2. Main steps for linking inductive and deductive analyses to derive a nested archetype classification. Panel A (yellow box): data-driven analysis for detecting and mapping typical social-ecological systems (SESs) and changes (SECHs) therein. Panel B (orange box): deductive assessment of typical SESs and SECHs to derive a nested archetype classification. The first nested level (dashed line) categorizes SESs according to their biophysical connectedness (Dorninger et al., 2017). The second nested level (solid line) groups archetypes further according to their potential material and/or experiential connectedness with nature (Cumming et al., 2014). Blue, yellow, and red boxes (panel B) represent high, intermediate, and low levels of connectedness of the deductive types. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sustainability and governance challenges in our study area. For instance, some SECHs could be leading SESs to a regime shift, or push them towards social-ecological traps (i.e., an undesirable state maintained by persistent and mutually reinforcing social and ecological feedbacks; Boonstra & de Boer, 2014). In this sense, *sensu* Cumming et al. (2014), ecological degradation due to inadequate food production can push a *green-loop* system to a *green-trap* situation, whereas overcrowding, ecological decline and overconsumption in a *red-loop* system can produce a *red-trap*.

3. Results

3.1. Detecting and mapping typical SESs and their changes

We identified and mapped 15 typical social-ecological systems (Fig. 3A; Appendix B, Table B.1). SESs principally influenced by agriculture (SES04-SES13) were widespread across the region (68% coverage), differing mainly in the type of activity (cropping or stockbreeding), cropland area, and cropland productivity (Appendix B, Table B.3). SESs dominated by natural areas (SES01-SES03; 29% coverage) were the least densely populated systems and principally located in mountainous areas across Andalusia. These SESs mainly differed in terms of environmental characteristics (e.g., precipitation, temperature, net primary productivity). Finally, SESs dominated by urban areas (SES14-SES15; 2.6% coverage) had the highest share of artificial surface, highest population densities, and highest greenhouse gas emissions. Social variables were especially important in describing these SESs (e.g., population age, income).

Assessing social-ecological changes yielded 12 major types of trends (Fig. 3B; Appendix B, Table B.2). SECHs lead by agricultural expansion and/or intensification (from SECH01 to SECH05) were widespread across our study region (46% coverage). These changes included strong

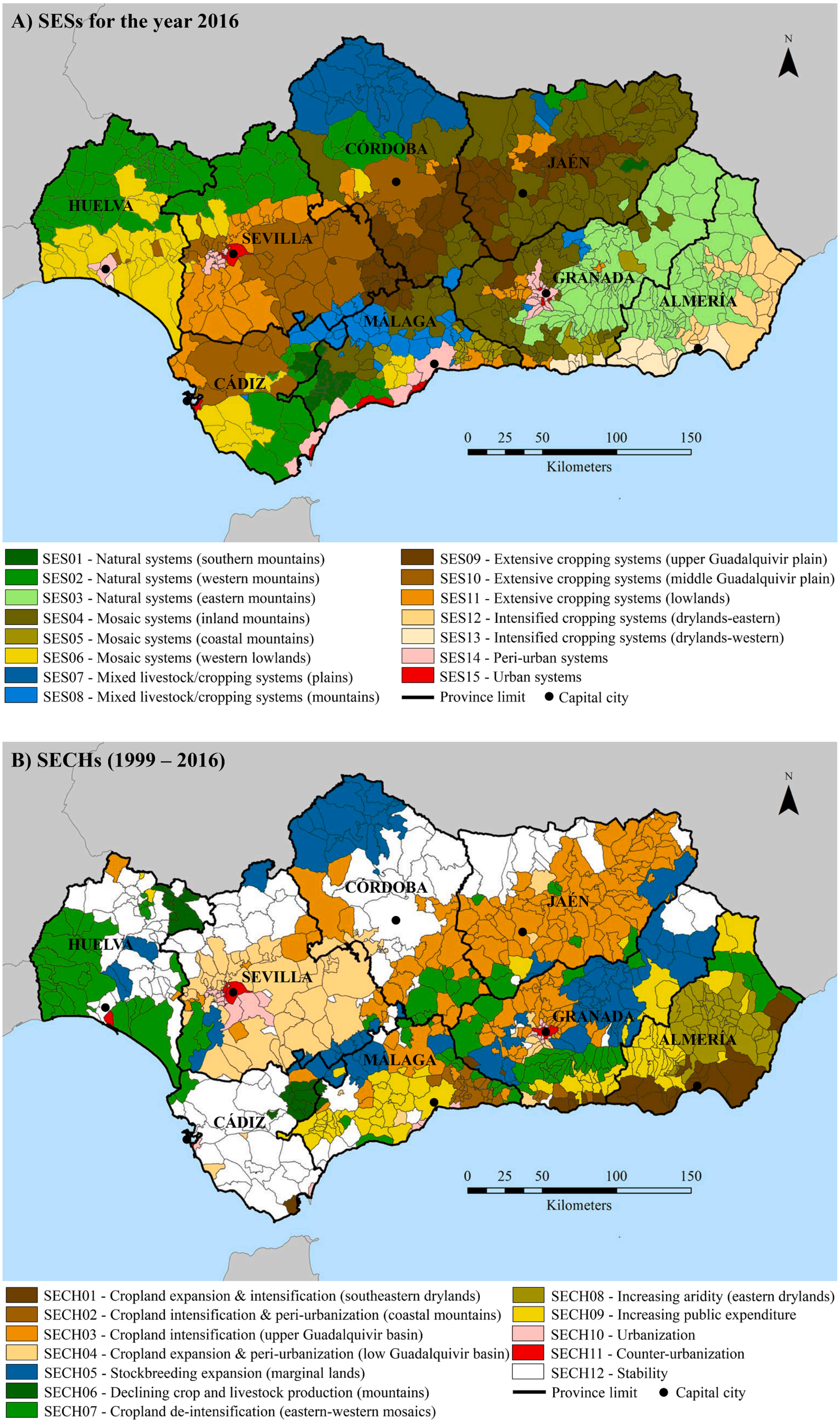

Fig. 3. Spatial patterns of typical social-ecological systems (SESs) for the year 2016 (A) and social-ecological changes (SECHs) between 1999 and 2016 (B) of Andalusia (Spain). Please refer to Appendix B, Tables B.1 and B.2 for a description of all SESs and SECHs.

increases in cropland productivity, irrigation agriculture, and livestock production, or the expansion of cropland area, which in some cases coexisted with the *peri*-urbanization process (Appendix B, Fig. B.1). Other SECHs represented declines in agricultural activities (14% coverage), encompassing both areas where livestock and crop production decreased (SECH06) and those where the surface of irrigated crops was reduced (SECH07). Some SECHs captured mainly changes in biophysical conditions (i.e., increase in aridity -SECH08-; 3.6% coverage) or social aspects (i.e., increase in public expenditure -SECH09-; 7.6% coverage). Other SECHs referred to areas affected by ongoing

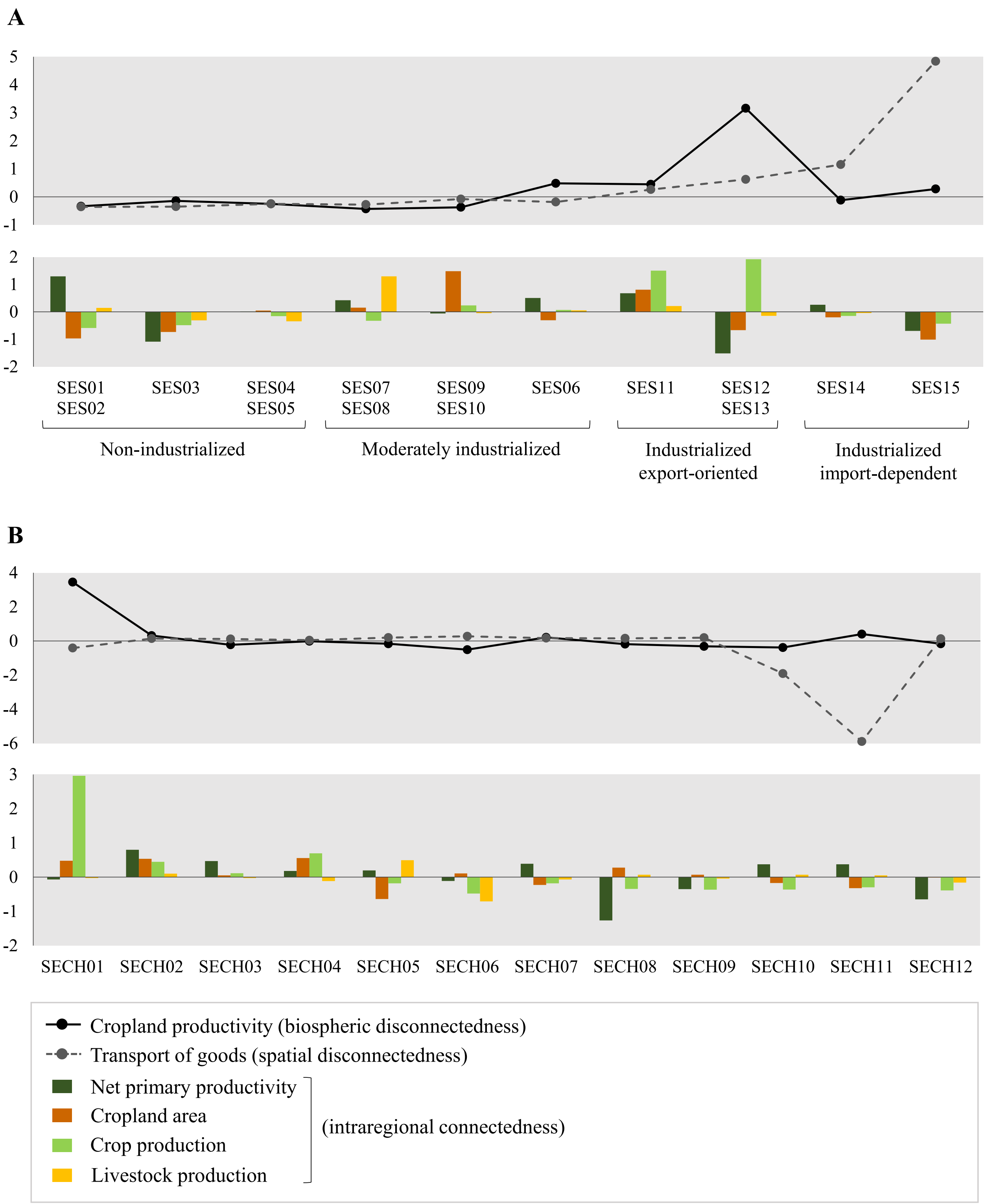

Fig. 4. Assessment of the dimensions of biophysical connectedness for the typical SESs of Andalusia (2016) (A), and variations in dimensions associated to typical SECHs (1999–2016) (B). Black solid line indicates cropland productivity levels as a proxy for biospheric disconnectedness (high productivity = high disconnectedness). Gray dashed line indicates the transport of goods as a proxy for spatial disconnectedness. Colour bars gather proxies of human appropriation of net primary production to indicate intraregional connectedness, as the baseline for comparing among SESs. All values are z-normalized (0 mean, 1 SD) to allow for comparison.

urbanization (0.9% coverage), indicating an increase in artificial surface, population density, and greenhouse gas emissions (SECH10), but also by counter-urbanization (i.e., urban de-concentration; 0.3% coverage), revealing a reduction in population density and associated greenhouse gas emissions (SECH11). Finally, the most widespread, single SECH (27% coverage) described stable areas (SECH12) and occurred throughout the region.

Analysing the spatial overlap between SESs and SECHs revealed typical associations between them (Appendix B, Fig. B.2). We found that stability (SECH12) had the largest spatial extent (Appendix B, Table B.4), affecting 10 out of 15 identified typical SESs, mostly natural ones (e.g., SES02), but also SESs dominated by agricultural areas such as mosaic systems (e.g., SES06), extensive cropping systems (e.g., SES10) and mixed livestock/cropping systems (e.g., SES07). From the perspective of SESs (Appendix B, Fig. B.2A), typical associations showed that agricultural SESs were mostly influenced by agricultural expansion and intensification trends, for instance, cropland intensification (SECH03) on mosaic and extensive cropping systems with olive grove fields (SES04 and SES09), or both cropland expansion and intensification (SECH01) on intensified cropping systems of drylands (SES12 and SES13). Similarly, stockbreeding expansion (SECH05) characterized mixed livestock/cropping systems (SES07 and SES08). Cropland expansion also co-occurred with *peri*-urbanization (SECH04) in extensive cropping systems of main river plains (SES10 and SES11). Other agricultural SESs were mainly influenced by changes in social aspects, such as the increase in public expenditure (SECH09) on mosaic systems of southern coastal mountains (SES05). Some SESs dominated by natural areas (e.g., SES01) were also influenced by this trend (SECH09), as well as by the decline of agricultural production (SECH06). In addition, from the perspective of SECHs (Appendix B, Fig. B.2B), typical associations revealed that cropland intensification and *peri*-urbanization (SECH02) mainly occurred in mosaic systems of southern coastal mountains (SES05), and that changes in biophysical conditions (i.e., increasing aridity -SECH08) principally affected the most arid systems, both natural (SES03) and intensified cropping systems (SES12). Finally, whereas urbanization (SECH10) mainly affected extensive cropping systems in the low Guadalquivir plain (SES10), the counter-urbanization trend (SECH11) was associated with *peri*-urban and urban systems (SES14 and SES15).

3.2. *Deductive assessment of archetypes*

Assessing the inductively identified typical SESs based on our two-level, nested scheme of deductive types revealed a gradient of human-nature connectedness across our study area. At the first level, we found that natural systems (SES01, SES02 and SES03) and the mosaic systems SES04 and SES05 showed a low intraregional connectedness, along with low biospheric and spatial disconnectedness (Fig. 4A). Thus, these SESs reflected the highest biophysical connectedness and were classified as *non-industrialized* (Fig. 2B). The mosaic system SES06 showed higher biospheric disconnectedness, while mixed livestock/cropping systems (SES07 and SES08) and the extensive cropping systems SES09 and SES10 maximized intraregional connectedness in terms of livestock production and cropland area. Therefore, these SESs reflected a lower biophysical connectedness and were classified as *moderately industrialized*. In the extensive cropping system SES11 and specially in intensified cropping systems (SES12 and SES13), a high intraregional connectedness in terms of crop production co-occurred with the highest biospheric disconnectedness and a high spatial disconnectedness. In this case, these SESs evidenced the lowest biophysical connectedness and were classified as *industrialized export-oriented*. Finally, in *peri*-urban and urban systems (SES14 and SES15), we found the highest spatial disconnectedness levels, which also reflected a low biophysical connectedness. However, these SESs were encompassed within the *industrialized import-dependent* category due to the lower intraregional connectedness and biospheric disconnectedness levels.

Regarding the variations in biophysical connectedness represented by SECHs (Fig. 4B), the most relevant changes were associated with cropland expansion and intensification (SECH01) and with urbanization and counter-urbanization trends (SECH10 and SECH11). Specifically, SECH01 reflected declining biophysical connectedness due to increases in biospheric disconnectedness and intraregional connectedness (in terms of crop production). In contrast, SECH10 and specially SECH11 reflected increasing biophysical connectedness due to a decline in spatial disconnectedness. In the remaining SECHs, variations in the biophysical connectedness did not substantially deviate from the study area average.

Categorizing typical SESs further in our second-level classification revealed that SES01 to SES13, dominated by natural or cropland cover (Appendix B, Fig. B.3), represented *green-loop* SESs (i.e., high potential material and/or experiential human-nature connectedness; Fig. 5). On the other side, SES15, dominated by artificial surfaces, exemplified a *red-loop* SES, i.e., highly urbanized systems, with lower connectedness. Finally, SES14, despite also representing an *industrialized import-dependent* system (as SES15), showed a balance among natural, cropland, and artificial surfaces, and was classified as a *transition* SES, i.e., intermediate connectedness. Overall, our two-level, nested scheme showed that natural systems (SES01-SES03) and mosaic systems SES04 and SES05 had the highest human-nature connectedness (i.e., high material and/or experiential connectedness and high biophysical connectedness). Such connectedness declined throughout the rest of agricultural SESs (i.e., high material and/or experiential connectedness, but lower biophysical connectedness), to a minimum in *peri*-urban and urban systems (SES15) (i.e., low material and experiential connectedness and low biophysical connectedness).

4. Discussion

Understanding archetypical patterns and changes in social-ecological systems (SESs) is important for organizing the complexity of social-ecological processes influencing landscape change, and thus ultimately for furthering theory in landscape and sustainability science (Eisenack et al., 2019). Both inductive and deductive perspectives have their particular strengths for this purpose, but methodologies that combine them are scarce. Here, we developed such a methodology and exemplify it for the region of Andalusia (Spain). Our approach first inductively detects and maps typical SESs and their changes, and second deductively interprets them with regard to human-nature connectedness. This yielded three key types of insights. First, we identified clear combinations of typical SESs and the social-ecological changes (SECHs) that contributed to shaping them. Second, we revealed a gradient of human-nature connectedness across the identified SESs, as well as key patterns of social-ecological changes that produce and enforce this gradient. Third, our approach allowed us to identify signals of ongoing regime shifts and trajectories towards social-ecological traps. This, in turn, allowed us to map areas that likely face specific sustainability challenges and thus likely require context-specific, spatially targeted policy responses.

4.1. *Describing typical social-ecological changes improve SES characterization*

The incorporation of a spatio-temporal perspective helped to characterize SESs in our study region. First, measuring the proportion of land occupied by agricultural, natural, and urban areas was key in differentiating between SESs. For instance, SESs dominated by agriculture were widespread across the region and mainly characterized by the principal land use (cropping or stockbreeding), the extent of cropping systems, and intensity. Importantly, diverse intensification trends influenced our agricultural SESs (Fig. 3; Appendix B, Fig. B.2). This supports views that intensification has been the central land-use change in Andalusia recently (Muñoz-Rojas et al., 2011), particularly the expansion of

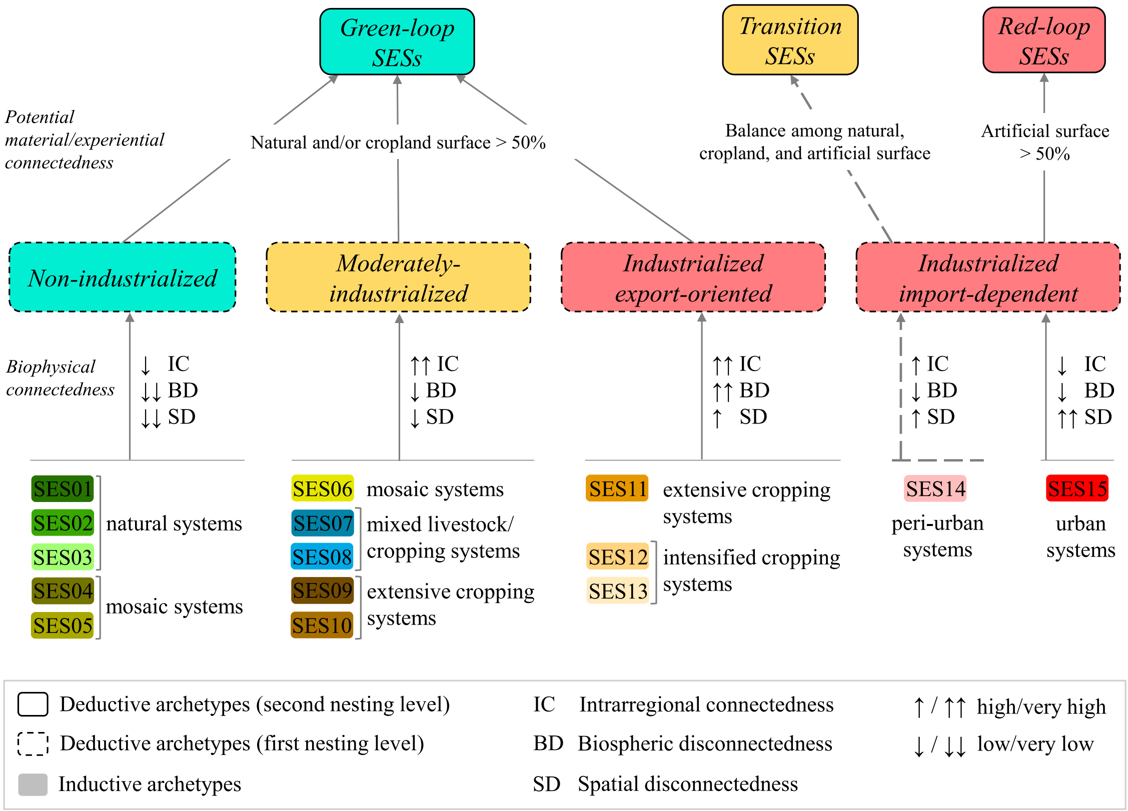

Fig. 5. Summary of the nested classification of inductive typical SESs within the deductive types proposed by Dorninger et al. (2017) and Cumming et al. (2014). Blue, yellow, and red boxes represent high, intermediate, and low levels of biophysical connectedness and potential material and/or experiential connectedness of the deductive types (following the colour code from Fig. 2B in methods section). The criteria used to differentiate among deductive types are shown along the arrows. Please note that dashed-line arrow is used to better differentiate between the two types of *industrialized import-dependent* systems. Background colour for inductive SESs follows the colour code of Fig. 3A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

irrigated crops (e.g., olive groves, fruit trees, and greenhouse horticulture) at the expense of traditional, non-irrigated cropland (Stellmes et al., 2013). Conversely, both de-intensification and agricultural decline also occurred in our region, as elsewhere in Mediterranean landscapes (Caraveli, 2000; Muñoz-Rojas et al., 2011). In addition, we found contrasting processes such as urbanization occurring in cropping systems next to the main urban SESs, while *peri*-urbanization was more diffuse and co-occurred with cropland expansion and intensification over mosaic and extensive cropping systems. The former reflects the mere expansion of cities, while the latter might indicate a “naturbanization” process via the movement of people from urban to rural areas, in search of a quieter lifestyle more in contact with nature (Pallarès-Blanch et al., 2014; Prados, 2009). Finally, the decrease in population density and in greenhouse gas emissions that affected some urban and *peri*-urban SESs reflects a shift to a more deconcentrated state, suggesting a counter-urbanization process (Mitchell, 2004). The highly spatially heterogenous nature of these changes underlines the need for spatially detailed data on social-ecological change.

To our knowledge, the few existing studies mapping SESs over time focused on changes in spatial distribution only (e.g., Renard et al., 2015), but rarely on how social-ecological change affects SESs themselves (Oberlack et al., 2019). Here, we used a holistic perspective that incorporates multiple dimensions of SESs (Pacheco-Romero et al., 2020) across the social and ecological system, as well as the interactions between them (Liu et al., 2007; Reyers et al., 2017). In line with recent SES studies (e.g., Dressel et al., 2018; Rocha et al., 2020; Vallejos et al., 2020), we used an existing conceptual SES framework (Pacheco-Romero et al., 2020) to organize indicators and to characterize the identified types with the aim of promoting: 1) comprehensiveness (Meyfroidt et al., 2018; Rocha et al., 2020); 2) knowledge comparison and generalization (Dressel et al., 2018; Partelow, 2018); and 3) the credibility and salience of the analysis (van Oudenhoven et al., 2018). We suggest that the combination of a temporal dimension and comprehensiveness represents a major step towards capturing the full complexity of SES mapping to inform resource management and landscape planning (Hamann et al., 2015; Levers et al., 2018).

4.2. Gradients of human-nature connectedness

Analysing our typical SESs through the deductive types proposed by Dorninger et al. (2017) and Cumming et al. (2014) provided substantial additional interpretive power. First, we found that the levels of intraregional connectedness, biospheric disconnectedness, and spatial disconnectedness across our SESs represented a range of industrialization levels, and therefore evidenced distinct degrees of biophysical connectedness (i.e., the degree of coupling with the natural productivity of the immediate regional environment). Second, the contrasting dominance of land covers in our SESs (from natural to agricultural and artificial surfaces) suggested different levels of potential material and/or experiential connectedness. It is worth noting that *green-loop* and *non-industrialized* systems were originally conceptualized as strict agricultural subsistence systems of developing regions (Cumming et al., 2014; Dorninger et al., 2017), while *red-loop* and *industrialized* systems represented urban systems but also rural areas in the developed world (Hamann et al., 2015). According to these approaches, our region would have been homogeneously conceptualized as a *red-loop*, *industrialized* system. However, our approach expanded the *green-loop* archetype to encompass SESs dominated by both natural or agricultural areas, while the *red-loop* archetype characterized urban SESs. Thus, the high material and/or experiential connectedness that characterizes *green-loop* SESs was linked to natural and agricultural systems that showed different levels of biophysical connectedness (from *non-industrialized* to *industrialized export-oriented*), which can have distinct management and sustainability implications. As a result, linking these deductive classifications to our typical SES via our nested hierarchy (Fig. 5) allowed us to unpack the diversity of human-nature connectedness dynamics across a rural–urban gradient of a region in a developed country. Using any one of these classifications alone would not have resulted in such a nuanced depiction of SES in the study region. Finally, incorporating the temporal dimension was fundamental to identify changes in biophysical connectedness, mainly associated with land use (Balázsi et al., 2019) (e.g., intensification) and counter-urbanization, and in material and/or experiential connectedness, associated with (*peri-*) urbanization.

To our knowledge, our study is the first to apply a nested archetype analysis which brings together inductively, data-driven archetype analyses to map SESs with deductive analyses for assessing human-nature connectedness (both biophysical and potential material/experiential connectedness). In addition, the study of such "external" connections and their changes may constitute a first step to understand further cognitive, emotional and philosophical human-nature connections, whose knowledge might reveal essential points of intervention (i.e. "leverage points") for reconnecting society with the biosphere and informing transitional pathways towards the sustainability of SES (Folke et al., 2011; Ives et al., 2017, 2018; Balázsi et al., 2019). Overall, our approach can thus contribute to enhancing SES archetype analyses by 1) integrating different levels of abstraction (Oberlack et al., 2019) that keep the context specificity of regional SES diversity while linking to

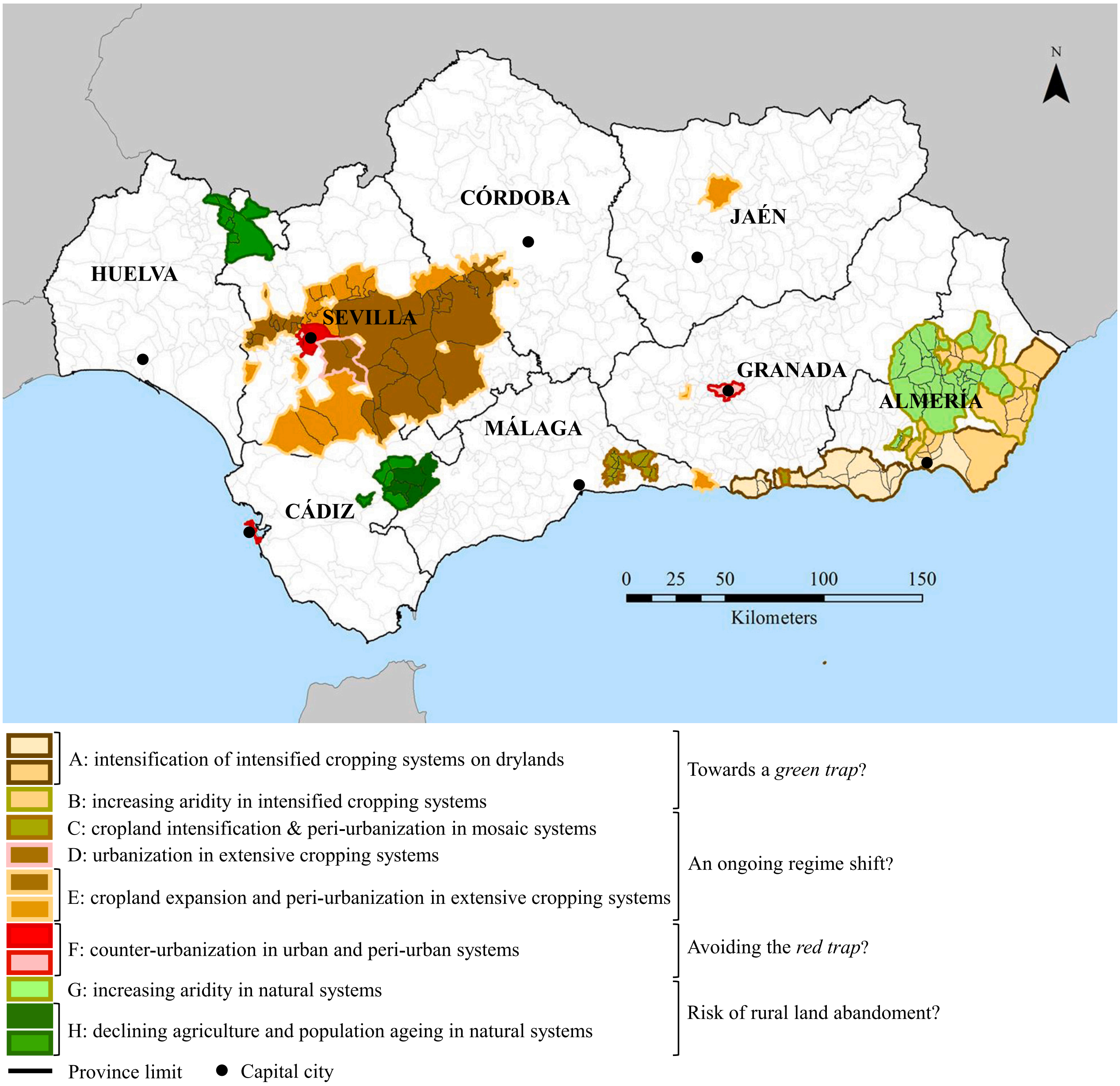

Fig. 6. Spatial patterns of potential sustainability challenges (A-H) based on co-occurring SECHs and SESs. Description of the challenges indicates the typical SECH affecting each SES (please refer to Appendix B, Table B.5). Background colour for SESs follows the colour code of Fig. 3A, while line colour indicates the specific SECH affecting to each SES, following the colour code of Fig. 3B.

globally recognisable, generic archetypes; 2) generating more potentially comparable and transferable insights across scales and contexts (Eisenack et al., 2019; Sietz et al., 2019); and 3) improving the usefulness and adaptability of archetypes to support territorial and resource use planning (Hamann et al., 2015; Sietz et al., 2017; Vallejos et al., 2020), considering SESs as units of management at regional scale (Dorninger et al., 2017).

4.3. Implications for sustainability and governance challenges

Integrating the interpretation of our typical SESs and SECHs according to human-nature connectedness with the results of the spatial overlap between them provided insights to identify major sustainability challenges in Andalusia (Fig. 6; Appendix B, Table B.5). Here we highlight some examples of how these challenges could relate to potential ongoing regime shifts and trajectories towards social-ecological traps. Overall, SESs dominated by agricultural areas received the main human pressures. For instance, the intensification of already intensively managed cropping systems on drylands (Fig. 6, challenge A), as well as the increasing aridity in these systems (challenge B), evidenced a growing biophysical disconnectedness over a territory with high water deficit and high material human-nature connectedness. Thus, these *industrialized export-oriented green-loop* SESs could be facing a *dust-bowl* syndrome (Lüdeke et al., 2004; Stellmes et al., 2013), where the non-sustainable agro-industrial use of soil and water feeds back into environmental degradation and may lead the system to collapse into a *green-trap* (*sensu* Cumming et al., 2014; Castro et al., 2019). Here, policy interventions should focus on pathways to sustainable intensification through technological innovations that do not compromise agriculture in the long-term (Rasmussen et al., 2018). In some mosaic systems, the increase in biophysical disconnectedness caused by cropland intensification and *peri*-urbanization (C) might underlie an ongoing regime shift from a *non-industrialized* to a *moderately industrialized green-loop* SES. Here, management strategies should prevent soil and water resources degradation, ensuring a fair transition that avoids the alienation of small producers and family farms (Tittonell, 2014), and the disappearance of traditional cropping systems and their associated cultural heritage (Malek & Verburg, 2017). In extensive cropping systems, urbanization (D) and the co-occurrence of cropland expansion with *peri*-urbanization (E) might foster an overall decrease of human-nature connectedness (Ives et al., 2018; Balázsi et al., 2019) and lead to a shift from *green-loop* to *transition* SESs. In this case, territorial planning should prevent a disproportionate increase in housing and urban areas, and promote people's experiential connection with the landscape in these rural areas (Balázsi et al., 2019; Sánchez-Zamora et al., 2014).

In urban and *peri*-urban systems, counter-urbanization (F) could be a rebound effect of urbanization and *peri*-urbanization processes in agricultural areas (Berry, 1980; Mitchell, 2004). Here, the decrease in population density and greenhouse gas emissions, driven by the probable movement of the population towards metropolitan and rural areas, may contribute to urban deconcentration (Pallarès-Blanch et al., 2014; Prados, 2009) and thus to "re-greening" the *red-loop* SES, preventing a collapse into a *red-trap* (*sensu* Cumming et al., 2014). Thus, the reduction of environmental pressures might be an opportunity to make more liveable cities and to foster the reconnection of urban population with the local environment. Finally, in natural areas, the main sustainability challenges could derive from the increasing aridity in mountainous eastern drylands (G), which might jeopardize the maintenance of traditional agricultural uses and associated knowledge, and therefore increase their vulnerability to desertification. In addition, some localized areas of natural systems in the western mountains faced a decline in agricultural production and an increase in population ageing (H). Both challenges (G, H) might lead to rural land abandonment (Serra et al., 2014) and to a weakening of human-nature connectedness. Here, policy efforts should enhance institutional mechanisms for rural development and for mitigation of climate change effects.

4.4. Limitations and potential follow-up work

Limitations of this study align with common challenges arising when dealing with complex systems. First, we tracked social-ecological change in space and time over a 17-year period, but a longer time period and a denser time series would be useful to further scrutinize how these changes alter the spatial distribution of SESs, or even lead to SES emergence or disappearance. Second, we worked at the level of municipalities, the smallest unit of policy relevance at which official statistics are typically available (Dorninger et al., 2017). Yet, finer granulation and/or multi-scale analyses could usefully extend this approach and resolve surprising outcomes such as urban areas (likely *red-loop* systems), that were embedded within wider *green-loop* systems. Third, although a comprehensive set of variables is needed to identify and characterize SESs and SECHs (Levers et al., 2018; Rocha et al., 2020; Vallejos et al., 2020), the resulting complexity can make it challenging to clearly interpret them. Developing a base set of essential social-ecological variables could further facilitate interpretation and cross-comparison (Cox et al., 2020; Pacheco-Romero et al., 2020). Likewise, additional variables would likely have refined our assessment, but were not available at sufficiently fine spatial and temporal resolution (e.g., rural–urban migrations, social equity, biodiversity, agricultural imports and exports). Fourth, we selected the number of clusters for SESs and SECHs based on our extensive knowledge of the study region, although applying a sensitivity analysis could have helped to determine the optimal number of clusters (Rocha et al., 2020). Finally, a more integrative analysis of human-nature connectedness that considers "internal" connections (i.e., cognitive, emotional, philosophical) could help to identify effective interventions for reconnecting people with nature and fostering the sustainability of SESs (Ives et al., 2018).

5. Conclusions

We developed a novel approach for characterising and mapping archetypical SESs that combines the strengths of both inductive and deductive perspectives. Applying this approach to the Andalusia region in Spain revealed 1) the typical SESs and key changes therein for this region, 2) a strong gradient of human-nature connectedness across SESs in that region, and 3) major sustainability challenges and where in the landscape they prevail. In addition to new and policy-relevant insights into SESs and their dynamics in our study region, our case study highlighted how our approach can be useful for archetype analyses more generally. Specifically, our methodology allows for 1) detecting major types of human-nature interactions that are unknown *a priori*, including novel interactions and social-ecological trade-offs, and 2) linking these inductive types to existing deductive classifications to improve the comparability of insights derived from SES research across regions, contexts and scales. Further, our study demonstrates how inductive, data-driven, bottom-up approaches can usefully be brought together with deductive approaches to organize the complexity and diversity of social-ecological characteristics, patterns, and interactions in a nested archetype classification. Finally, our approach supports the design of context-specific policies and land management, and helps to pinpoint where such management interventions should take place, to tackle challenges such as potential regime shifts or emerging social-ecological traps. This ultimately contributes to navigating SESs towards more sustainable pathways.

CRediT authorship contribution statement

Manuel Pacheco-Romero: Conceptualization, Methodology, Formal analysis, Writing - original draft, Funding acquisition. **Tobias Kuemmerle:** Conceptualization, Writing - original draft, Resources, Supervision. **Christian Levers:** Methodology, Software, Formal analysis, Writing - review & editing. **Domingo Alcaraz-Segura:** Writing - review & editing, Project administration, Funding acquisition. **Javier**

Cabello: Writing - review & editing, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104199.

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