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From theory to practice: conceptual and methodological advances to enhance comparability and knowledge generalization in social-ecological system research

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Memoria presentada por Manuel Pacheco Romero para optar al Grado de Doctor en Ciencias Aplicadas al Medio Ambiente por la Universidad de Almería.

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A mis padres, a mi hermana y a mi abuelo,

A Trini

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RESUMEN

El impacto de la actividad humana sobre el sistema Tierra ha alcanzado niveles sin precedentes a lo largo del último siglo, lo que ha llevado a reconocer el inicio del Antropoceno, una nueva era en la que la capacidad transformadora humana compite con la de las fuerzas geológicas. Estos impactos están ocasionando un cambio medioambiental global que ha sobrepasado los umbrales que definen el espacio operativo seguro para la humanidad. El progreso y bienestar de las sociedades humanas depende en última instancia de la existencia de sistemas naturales funcionales capaces de proveer bienes y servicios esenciales, tanto materiales como no materiales. Sin embargo, habitamos un planeta altamente interconectado, con interacciones a través de diferentes escalas que vinculan sociedades y ecosistemas distantes, y sobre el que los impactos tienen cada vez mayor alcance. Esto ha propiciado un desacoplamiento de la actividad humana de la dinámica de los sistemas naturales, y como consecuencia, un debilitamiento general de la conexión humanos-naturaleza. En general, las acciones desarrolladas para hacer frente a estos impactos han sido abordadas desde enfoques sectoriales y reduccionistas, y no están siendo suficientes para frenar la degradación ambiental y los efectos del cambio global. Incluso en el ámbito de la investigación, clave para desarrollar soluciones hacia la sostenibilidad, se aprecia esta sectorialidad, pues tradicionalmente las ciencias ecológicas y sociales han progresado por separado.

Necesitamos un cambio de paradigma. Abordar los desafíos medioambientales que plantea el Antropoceno requiere perspectivas holísticas que reconozcan la dependencia de las personas de la naturaleza y consideren las complejas interacciones que existen entre los sistemas humanos y naturales. El concepto de sistema socio-ecológico (SSE), que reconoce formalmente el acoplamiento entre los sistemas humanos y naturales, proporciona una aproximación fundamental para hacer frente a estos desafíos, y constituye un pilar básico para desarrollar las ciencias de la sostenibilidad. Desde que este concepto surgiera hace 22 años se han producido importantes avances en su desarrollo teórico y en la creación de marcos conceptuales, lo que ha favorecido su operacionalización en estudios empíricos (i.e., investigación socio-ecológica basada en el lugar). El conocimiento generado a partir de estos estudios es clave para entender las dinámicas socio-ecológicas a través de contextos y escalas, lo que resulta fundamental para abordar los desafíos de sostenibilidad global. Sin embargo, el pluralismo conceptual y metodológico que caracteriza a la investigación socio-ecológica puede obstaculizar la síntesis y comparación de los

resultados obtenidos. Por ello, es necesario desarrollar herramientas y aproximaciones que contribuyan a la consolidación metodológica y conceptual en la investigación sobre SSE. Así, el objetivo general de esta tesis es generar avances conceptuales y metodológicos para la operacionalización del concepto de sistema socio-ecológico en investigación empírica que favorezcan desarrollar conocimiento más comparable y generalizable a través de distintos contextos y escalas. Para ello, aportamos conocimiento a dos ámbitos fundamentales para la investigación socio-ecológica: (1) la identificación de variables clave para el estudio de los SSE, y (2) la cartografía y caracterización de arquetipos de SSE.

En la sección 2.1 de resultados nos centramos en el papel de los marcos conceptuales y listados de referencia de variables como guía o soporte para el desarrollo de investigación socio-ecológica basada en el lugar. Aunque hasta la fecha se han desarrollado varios marcos conceptuales, su uso en investigación empírica no está generalizado. Además, solo el marco conceptual del SSE de Ostrom incorporó un listado de referencia de variables. Aunque este marco ha sido uno de los más influyentes, son varios los trabajos que han reportado dificultades en su aplicación empírica. De hecho, aún queda mucho trabajo por delante para identificar las variables esenciales para la caracterización y seguimiento de los SSE, al igual que se está haciendo en el ámbito de la biodiversidad, el clima o los océanos. Para contribuir a este fin, realizamos un estudio basado en revisiones bibliográficas, talleres de expertos y percepciones de investigadores recogidas a través de encuestas en línea. Esto nos permitió desarrollar un listado de referencia de 60 variables para la caracterización y seguimiento de los SSE, estructuradas en un marco conceptual compuesto por 13 dimensiones distribuidas a través de los tres componentes del SSE: sistema social, sistema ecológico, e interacciones entre ambos. Para facilitar un uso flexible del listado, las variables fueron priorizadas de acuerdo con criterios de relevancia y consenso identificados a partir de las encuestas. A través de este trabajo aportamos nuevas perspectivas para abordar las barreras existentes en la operacionalización de listados de variables para el estudio de los SSE, tales como la aplicabilidad para la investigación basada en el lugar, la capacidad para lidiar con la complejidad de los SSE, y la viabilidad para el seguimiento a largo plazo de dinámicas socio-ecológicas. En general, disponer de listados de referencia operativos contribuye a promover la colección sistemática de datos, y a reforzar la comparabilidad del estudio y seguimiento de los SSE.

En la sección 2.2 de resultados nos centramos en el papel de la cartografía y caracterización de arquetipos de SSE para el desarrollo de la investigación socio-ecológica basada en el lugar. Los arquetipos de SSE se definen como combinaciones singulares de factores sociales, ecológicos y de interacción humanos naturaleza, con patrones que aparecen reiteradamente a través del territorio. Los trabajos de cartografía de SSE desarrollados en la última década muestran una gran pluralidad de aproximaciones, tanto en la conceptualización del SSE, como en las variables seleccionadas y la metodología aplicada. La tendencia apunta al uso de bases de datos cada vez más integradoras, así como de marcos conceptuales para estructurar las variables empleadas y guiar la caracterización de los sistemas identificados, lo cual favorece la comparabilidad de las investigaciones. Sin embargo, hasta ahora la selección de variables para la cartografía se ha realizado deliberadamente, en general condicionada por la disponibilidad de datos o los objetivos de investigación. Por ello, con el objetivo de mejorar el potencial de la cartografía de SSE para generar conocimiento empírico comparable sobre los factores que determinan la distribución y dinámica de los SSE, desarrollamos una aproximación metodológica para identificar las variables más relevantes en la detección y cartografía de la diversidad de SSE en regiones concretas. Tomando Andalucía (España) como caso de estudio, aplicamos una rutina metodológica basada en análisis estadísticos multivariantes a una base de datos extensa compuesta por 86 indicadores representativos de las variables, dimensiones y componentes del SSE derivados en la sección 2.1. También evaluamos cómo la relevancia empírica de estos indicadores contribuye al conocimiento experto (derivado de la sección 2.1) y empírico existente sobre variables clave para caracterizar SSE. Identificamos un conjunto de 29 indicadores clave en nuestra zona de estudio que nos permitieron cartografiar y caracterizar 15 arquetipos de SSE representativos de sistemas naturales, agrícolas, mosaico y urbanos, los cuales mostraron patrones contrastantes de *land sharing* y *land sparing* a través del territorio. Además, identificamos puntos de sinergia pero también de desacuerdo entre la relevancia de las variables percibida por expertos, y su relevancia empírica para cartografiar SSE (tanto en nuestro caso de estudio en Andalucía como en una selección de los principales estudios de cartografía de SSE a escala local, regional y global). Esta comparación evidenció uno de los actuales desafíos de la investigación sobre SSE: identificar qué variables son de relevancia universal, y cuáles son contexto-dependientes. En general, la aplicación de la rutina metodológica propuesta puede ayudar a acumular conocimiento empírico objetivo sobre variables clave para la cartografía de SSE a través de contextos y escalas, y a complementar las evaluaciones de expertos en la búsqueda de las variables esenciales para los SSE.

En la sección 2.3 de resultados exploramos el potencial de las clasificaciones deductivas de arquetipos para facilitar la comparación y generalización del conocimiento obtenido en los estudios de cartografía de SSE (i.e., identificación inductiva, aquella que se obtiene de forma empírica). Los arquetipos deductivos constituyen tipologías teóricas de SSE derivadas a partir de la observación de patrones de interacción y dinámicas socio-ecológicas recurrentes en el mundo, por lo que presentan un gran potencial para interpretar SSE. Así, con el objetivo de aprovechar las fortalezas que ofrecen las perspectivas inductiva y deductiva, desarrollamos una aproximación para el análisis anidado de arquetipos que retuviera la diversidad regional de SSE permitiendo a la vez las comparaciones a través de regiones. Para ello, tomamos una vez más Andalucía como caso de estudio, y utilizamos un enfoque inductivo espacio-temporal para identificar y cartografiar sus tipos de SSE en el año 2016 y de cambio socio-ecológico ocurridos en el periodo 1999-2016. Después los interpretamos a partir de dos enfoques de tipologías deductivas de conectividad humanos-naturaleza, obteniendo una clasificación anidada inductiva-deductiva de arquetipos. A través de este análisis encontramos claras combinaciones de SSE y cambios socio-ecológicos que les afectaron, así como un marcado gradiente de conectividad humanos-naturaleza a través de dichos SSE. Esto nos permitió identificar y cartografiar áreas que enfrentan desafíos de sostenibilidad específicos vinculados a cambios de régimen en curso, y trayectorias hacia trampas socio-ecológicas asociadas al decrecimiento de la conectividad humanos-naturaleza. Así, este enfoque integró diferentes niveles de abstracción, manteniendo la contexto-especificidad regional a la vez que vinculando con arquetipos genéricos globalmente reconocibles. Esto facilita la aplicación de respuestas de gestión contexto-específicas, pero también la formulación de políticas de mayor alcance.

En general, los avances conceptuales y metodológicos que proporciona esta tesis pueden contribuir a desarrollar enfoques más comparables en investigación socio-ecológica basada en el lugar y a impulsar la transferencia de conocimiento a través de contextos y escalas. El conocimiento generado contribuye a dos grandes desafíos de investigación fundamentales para integrar el enfoque socio-ecológico en el diseño de soluciones para enfrentar los desafíos de sostenibilidad en el Antropoceno: 1) identificar variables esenciales para el estudio y seguimiento de los SSE, y 2) mejorar la utilidad de los mapas de SSE para los procesos de planificación territorial contexto-específicos, pero también para informar discursos y estrategias políticas más globales.

ABSTRACT

The impact of human activity on the Earth system has reached unprecedented levels over the last century, leading to the recognition of the beginning of the Anthropocene, a new era in which the capacity of humans to transform the planet competes with geological forces. These impacts are causing a global environmental change that has overpassed the thresholds that define the safe operating space for humanity. The progress and well-being of human societies ultimately depends on the existence of functional natural systems capable of providing essential goods and services, both material and non-material. However, we inhabit a highly interconnected planet, with interactions across different scales linking distant societies and ecosystems, and where impacts are increasingly far-reaching. This has led to a decoupling of human activity from natural system dynamics, and consequently, to a general weakening of human-nature connectedness. In general, the actions developed to face these environmental impacts have been addressed from sectorial and reductionist approaches, and are not being enough to halt environmental degradation and global change effects. Even from research, which is key to develop solutions towards sustainability, such reductionism is evident, since traditionally the ecological and social sciences have progressed separately.

We need a paradigm shift. Addressing the environmental challenges in the Anthropocene requires holistic approaches that recognize people's dependence on nature and consider the complex interactions that exist between human and natural systems. The social-ecological system (SES) concept, which formally recognizes the coupling between human and natural systems, provides a fundamental approach to face these challenges, and constitutes a foundation for developing sustainability science. Since this concept emerged 22 years ago, there have been important advances in its theoretical development and in the creation of conceptual frameworks, which has favoured its operationalization in empirical studies (i.e., place-based social-ecological research). The knowledge generated from these studies is key to understanding social-ecological dynamics across contexts and scales, which is essential to address global sustainability challenges. However, the conceptual and methodological pluralism that characterizes social-ecological research can hinder the synthesis and comparison of results. Therefore, it is necessary to develop tools and approaches that contribute to the methodological and conceptual consolidation in SES research. Thus, the general objective of this thesis is to generate conceptual and methodological advances for the operationalization of the SES concept in empirical research that favours the development of more comparable and generalizable knowledge throughout different contexts and scales. To this end, we provide knowledge in two fundamental areas for social-ecological research: (1) the identification of key variables for the study of SESs, and (2) the mapping and characterization of SES archetypes.

In section 2.1 of results we focused on the role of conceptual frameworks and reference lists of variables to support the development of place-based social-ecological research. Although several conceptual frameworks have been developed to date, their use in empirical research is not widespread. Furthermore, only Ostrom's SES framework incorporated a reference list of variables. Although this framework has been one of the most influential, several studies have reported difficulties in its empirical application. In fact, much work is still needed to identify the essential variables for the characterization and monitoring of SESs, just as it is being done in the field of biodiversity, climate or oceans. To contribute to this end, we conducted a study based on literature reviews, expert workshops, and researchers' perceptions collected through online surveys. This allowed us to develop a reference list of 60 variables for the characterization and monitoring of SESs, structured in a conceptual framework composed of 13 dimensions distributed across the three components of the SES: social system, ecological system, and interactions between them. To facilitate a flexible use of the list, the variables were prioritized according to relevance and consensus criteria identified from the surveys. This study brings new perspectives to address existing barriers in operationalizing lists of variables in the study of SESs, such as the applicability for place-based research, the capacity to deal with SES complexity, and the feasibility for long-term monitoring of social-ecological dynamics. In general, having operational reference lists of variables contributes to promote the systematic collection of data, and to reinforce the comparability of the study and monitoring of SESs.

In section 2.2 of results we focused on the role of mapping and characterization of SES archetypes for the development of place-based social-ecological research. SES archetypes are unique combinations of social, ecological, and human-nature interaction factors, with patterns that appear repeatedly throughout the territory. The studies of SES mapping developed in the last decade show a great diversity of approaches, both in the conceptualization of the SESs, as well as in the selected variables and the applied methodology. The most recent studies are increasingly using integrative databases and

conceptual frameworks to structure the variables and guide the characterization of the identified SESs, which favours the comparability of research. However, until now the selection of variables for SES mapping has been deliberate, generally conditioned by data availability or the research goals. Therefore, with the aim of enhancing the potential of SES mapping to generate comparable empirical knowledge on the variables that determine their distribution and dynamics, we developed a methodological approach to identify the most relevant indicators for the detection and mapping of SES archetypes in specific regions. Taking Andalusia (Spain) as a case study, we applied a methodological routine based on multivariate statistical analysis to an extensive database composed of 86 indicators that represent the variables, dimensions and components of the SES derived in section 2.1. We also assess how the empirical relevance of these indicators contributes to the existing expert knowledge (derived from section 2.1) and empirical knowledge on key variables to characterize SESs. We identified 29 key indicators in our study area that allowed us to map and characterize 15 SES archetypes, which were representative of natural, agricultural, mosaic, and urban systems, and showed contrasting patterns of land sharing and land sparing across the territory. In addition, we identified points of synergy but also of disagreement between the relevance of the variables perceived by experts, and their empirical relevance for mapping SESs (both in our case study in Andalusia and in a selection of the main SES mapping studies at local, regional and global scales). This comparison highlighted one of the current challenges of SES research: identifying which variables are of universal relevance, and which are context-dependent. In general, the application of the proposed methodological routine can help to accumulate objective empirical knowledge on key variables for SES mapping across contexts and scales, and to support expert assessments in the search for essential SES variables.

In section 2.3 of results we explored the potential of deductive archetype classifications to facilitate the comparison and generalization of the knowledge obtained in SES mapping studies (i.e., inductive identification, empirically obtained). Deductive archetypes constitute theoretical typologies of SESs derived from the observation of recurrent interaction patterns and social-ecological dynamics throughout the world, thereby presenting a great potential to interpret SESs. Thus, to leverage the strengths of both inductive and deductive perspectives, we developed an approach for nested archetype analysis that retains the regional diversity of SESs while allowing for cross-comparison across regions. To this end, we took Andalusia as a case study, and applied an

inductive spatio-temporal approach to identify and map its typical SESs for 2016 and social-ecological changes for the period 1999-2016. Then, we interpreted them from two approaches of deductive typologies of human-nature connectedness, obtaining a nested inductive-deductive archetype classification. Through this analysis, we found clear combinations of SESs and social-ecological changes that affected them, as well as a gradient of human-nature connectedness across SESs. This allowed us to identify and map areas that face specific sustainability challenges linked to ongoing regime shifts and trajectories towards social-ecological traps associated with decreasing human-nature connectedness. Thus, this approach integrated different levels of abstraction, keeping regional context-specificity while linking to globally recognizable generic archetypes. This may facilitate the application of context-specific management responses, but also the formulation of broader policies.

In general, the conceptual and methodological advances of this thesis can contribute to the development of more comparable approaches in place-based social-ecological research and to foster knowledge transferability across contexts and scales. The knowledge produced contributes to two major research challenges that are fundamental to integrate the social-ecological approach in the design of solutions to face the sustainability challenges in the Anthropocene: 1) identifying essential variables for the study and monitoring of SES, and 2) enhancing the usefulness of SES mapping for context-specific territorial planning processes, but also for informing more global strategies and policy dialogues.

1. INTRODUCCIÓN

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1.1. Contexto

Las personas en la biosfera

El progreso y bienestar de la humanidad está ligado al correcto funcionamiento de los sistemas naturales, que suministran bienes y servicios esenciales a las sociedades humanas. Los sistemas naturales proporcionan el espacio físico sobre el que los sistemas humanos se asientan, construyen edificaciones e infraestructuras, y desarrollan sus actividades productivas (Daily, 1997; MA, 2005). Para ello, los humanos consumen o reciben las contribuciones materiales (p. ej., alimentos, agua y resto de materias primas), y no materiales (p.ej., servicios de regulación hídrica, polinización, disfrute de la naturaleza, inspiración artística o intelectual, etc.) que los ecosistemas les aportan (Díaz et al., 2018; Pascual et al., 2017). El impacto de la actividad de las personas sobre los sistemas naturales no ha dejado de aumentar desde que se conformaron las primeras sociedades (Rockström et al., 2009). Al principio, los humanos eran cazadores-recolectores, consumían lo que los sistemas naturales más próximos les proporcionaban, y se desplazaban hacia otros lugares a medida que los recursos escaseaban. Por ello, la subsistencia de estas comunidades era altamente dependiente de los recursos locales, y su actividad producía un bajo impacto en los ecosistemas (Cumming et al., 2014).

A partir de la Revolución Industrial, el desarrollo de la agricultura y de los avances tecnológicos, junto con un creciente consumo de combustibles fósiles, permitió a las sociedades humanas intensificar su capacidad para transformar la naturaleza (Rockström et al., 2009; Vitousek et al., 1997). Se comenzó a extraer recursos de lugares cada vez menos accesibles y más distantes, y se industrializó la producción agrícola a base de insumos externos (agroquímicos) y maquinaria. El desarrollo del comercio global permitió el intercambio de productos que eran consumidos en lugares lejanos de donde eran producidos. Así, la dependencia de los sistemas humanos de los recursos naturales locales disminuyó, especialmente en las sociedades más industrializadas, y los impactos derivados de su actividad aumentaron exponencialmente y se expandieron hacia lugares cada vez más distantes (Cumming et al., 2014). Hoy, la humanidad habita un planeta altamente interconectado, o “teleacoplado” (Liu et al., 2013), con interacciones a través de diferentes escalas que vinculan sociedades y ecosistemas distantes, lo que está originando desigualdades intra e interterritoriales (Martín-López et al., 2020). Paralelamente, el desacoplamiento de la actividad humana de la dinámica de sus sistemas naturales más próximos se ha traducido en un debilitamiento de la conexión humanos-naturaleza, tanto en la dimensión material como cognitiva y emocional (Ives et al., 2018). En consecuencia, en muchas sociedades (sobre todo occidentales) las personas han dejado de percibir que su bienestar depende de preservar ecosistemas funcionales y un medioambiente saludable (Folke et al., 2011).

En la actualidad, asistimos a un desafío medioambiental sin precedentes. Las acciones humanas se han convertido en el principal motor del cambio global (Steffen et al., 2007), marcando el inicio del Antropoceno (Crutzen, 2002). El Antropoceno se ha definido como una nueva época geológica donde la capacidad de la actividad humana para influenciar la trayectoria del sistema Tierra compite con la de las fuerzas geológicas (Steffen et al., 2018). Estos cambios están sacando al planeta de la relativa estabilidad climática que ha caracterizado al Holoceno. Recientes investigaciones señalan que hemos sobrepasado el umbral de cambio seguro en algunos procesos críticos que regulan el funcionamiento del sistema Tierra, como los ciclos biogeoquímicos del fósforo y del nitrógeno, o la integridad de la biosfera (Rockström et al., 2009; Steffen et al., 2015). Para frenar y revertir estos cambios (p.ej., en el clima, biodiversidad, cobertura terrestre), se han dado pasos importantes, como por ejemplo la declaración de áreas protegidas terrestres y marinas, la prohibición de sustancias causantes del agujero en la capa de ozono, o el fomento del uso de energías renovables. Sin embargo, estas iniciativas, que en ocasiones son abordadas desde enfoques sectoriales y reduccionistas, no están siendo suficientes para frenar la degradación ambiental y los efectos del cambio global (Liu et al., 2015; Steffen et al., 2011). Incluso en el ámbito de la investigación, que es clave para desarrollar soluciones hacia la sostenibilidad, se aprecia esta sectorialidad, pues tradicionalmente las ciencias ecológicas y sociales han progresado por separado (Liu et al., 2007a; Ostrom et al., 2009). En consecuencia, los esfuerzos realizados desde la gestión y la investigación están poco coordinados, focalizan en los componentes del sistema Tierra de forma aislada (e.g., aire, biodiversidad, energía, agua, personas), y pueden llegar a generar resultados contraproducentes (Liu et al., 2015).

Cada vez es mayor la evidencia científica acumulada que aboga por la necesidad de un cambio de paradigma hacia una visión integrada de los sistemas humanos y naturales que permita hacer frente a los desafíos de sostenibilidad global (Díaz et al., 2015; Liu et al., 2015). Así, abordar los retos medioambientales que plantea el Antropoceno requiere perspectivas holísticas que reconozcan la dependencia de las personas de la naturaleza y consideren las complejas interacciones que existen entre los sistemas humanos y naturales (Folke et al., 2011; Liu et al., 2007b).

Los sistemas socio-ecológicos

Con el reconocimiento formal de que el ser humano forma parte de la naturaleza y que los sistemas humanos y naturales están acoplados surgió el concepto de sistema socio-ecológico (SSE) (Berkes & Folke, 1998). Los SSE son sistemas complejos y adaptativos integrados en los que las personas interactúan con los componentes biofísicos de la biosfera a través de múltiples escalas temporales y espaciales (Liu et al., 2007a; Ostrom et al., 2009). Así, las investigaciones desarrolladas en el marco de los SSE consideran no solo los componentes humano y ecológico, sino también las interacciones que existen entre ellos (Resilience Alliance, 2007). La perspectiva socio-ecológica ha abierto la puerta a un cambio de paradigma en el que es necesario integrar las ciencias ecológicas y las ciencias sociales (Herrero-Jáuregui et al., 2018). Dicha integración es clave para abordar la complejidad, magnitud y rapidez de los cambios en las interacciones humanos-naturaleza que están teniendo lugar en el Antropoceno (Liu et al., 2007b). Así, los SSE ofrecen una aproximación fundamental desde la que desarrollar las ciencias de la sostenibilidad (Fischer et al., 2015).

Desde que el concepto de SSE surgiera hace 22 años (Berkes & Folke, 1998) se han producido importantes avances en el desarrollo teórico de dicho concepto, en la creación de marcos conceptuales y en su aplicación a la investigación empírica (de Vos et al., 2019). En el desarrollo teórico, múltiples estudios (p. ej., Berkes et al., 2003; Chapin et al., 2009; Liu et al., 2007b; Preiser et al., 2018) han contribuido a explicar los patrones y procesos que emergen de las interacciones humanos-naturaleza, y a conceptualizar a los SSE como sistemas complejos adaptativos. Así, según Preiser et al. (2018), los SSE: 1) se definen relacionalmente, es decir, a partir de las interacciones entre los componentes que los constituyen, y las interacciones entre el sistema y el exterior; 2) tienen capacidades adaptativas, es decir, se adaptan en respuesta a cambios que ocurren en dichas interacciones; 3) muestran una dinámica no lineal, lo que indica que la magnitud de las respuestas que genera el sistema no es proporcional a la magnitud de sus causas; 4) son abiertos, permeables, lo que implica que intercambian energía, información y materia con el exterior; 5) están determinados contextualmente, es decir, los cambios en el contexto en el que se encuentran embebidos pueden inducir cambios en el funcionamiento del sistema; y 6) muestran propiedades emergentes, es decir, su comportamiento no puede comprenderse o predecirse solo a partir de las propiedades de sus componentes individuales. Estas características de los SSE permiten entender otros aspectos fundamentales para abordar su estudio, tales como los acoplamientos a través de escalas temporales y espaciales, la resiliencia o la vulnerabilidad (Herrero-Jáuregui et al., 2018; Liu et al., 2007b). En general, la complejidad inherente al funcionamiento de los SSE dificulta predecir las consecuencias de los cambios que en ellos se producen. Esta complejidad también dificulta determinar los límites espaciales de los SSE, es decir, decidir qué está dentro y qué está fuera del sistema, pues depende del observador (Preiser et al., 2018). Estas cuestiones desafían la operacionalización de este concepto en investigación empírica.

Para hacer frente a estos desafíos, el desarrollo de marcos conceptuales ha sido clave en la operacionalización del concepto de SSE. Los marcos conceptuales comprenden colecciones de conceptos relevantes para analizar un fenómeno, y actúan como lentes a través de las que mirar la realidad (McGinnis, 2011). A su vez, facilitan el uso de un lenguaje compartido, proporcionando una terminología y estructura analítica común para las variables y componentes analizados en un sistema, indicando las relaciones estructurales entre ellos (Díaz et al., 2015; Meyfroidt et al., 2018). Son varios los marcos desarrollados para conceptualizar los SSE (p.ej., Anderies et al., 2004; Chapin, 2006; Collins et al., 2011; Folke & Berkes, 1998; MA, 2005; Ostrom, 2009; Resilience Alliance, 2007), y generalmente representan los componentes social y ecológico, así como las interacciones entre ellos (Díaz et al., 2015). Entre los más trascendentales se encuentra el marco conceptual del SSE de Elinor Ostrom, publicado en la revista Science en 2009, que fue concebido para diagnosticar la sostenibilidad de estos sistemas, y del que destaca la incorporación de un listado de variables clave estructuradas jerárquicamente.

Los listados de referencia de variables clave complementarios a los marcos conceptuales contribuyen a organizar los análisis y desarrollar estudios más comparables (Colding & Barthel., 2019; Ostrom, 2009; Partelow, 2018). Dichos listados ayudan a mejorar la comunicación y el uso de un lenguaje compartido de cara a coordinar esfuerzos multidisciplinares para el seguimiento y caracterización de SSE (Cox et al., 2020; Ostrom, 2009). El interés científico por crear listados de variables de referencia que capturen dimensiones críticas del sistema Tierra se ha hecho evidente en ámbitos como el clima (Bojinski et al., 2014), los océanos (Constable et al., 2016) y la biodiversidad (Pereira et al., 2013), en los que ya se dispone de listados de variables esenciales bastante consolidados. En el ámbito de los SSE, aparte del listado de Ostrom, existen otras iniciativas que están avanzando en la construcción de conjuntos de variables clave, por ejemplo, para el seguimiento de los límites planetarios (Rockström et al., 2009; Steffen et al., 2015), de los Objetivos de Desarrollo Sostenible (Reyers et al., 2017), de áreas protegidas (Guerra et al., 2019), o de los servicios de los ecosistemas (Balvanera et al., 2016). Aun así, queda mucho camino por recorrer para desarrollar un listado de variables esenciales de los SSE estandarizado y coordinado, equiparable al de ámbitos como el clima y la biodiversidad.

Finalmente, otros estudios han llevado el concepto de SSE a la práctica, lo que se conoce como investigación socio-ecológica basada en el lugar o *"place-based social-ecological research"* (Balvanera et al., 2017a). En contraste con los estudios teóricos o los que desarrollan marcos conceptuales, los estudios de investigación socio-ecológica basada en el lugar son los más importantes en número de trabajos publicados (de Vos et al., 2019; Herrero-Jáuregui et al., 2018). De hecho, la investigación socio-ecológica emergió a partir de estudios empíricos a escala local (Colding & Barthel, 2019), aunque hoy en día se realizan también a escala regional, nacional, multinacional y global (de Vos et al., 2019). En general, las metodologías utilizadas en estos estudios son muy diversas y suelen aplicarse a SSE concretos delimitados espacialmente de forma arbitraria (Herrero-Jáuregui et al., 2018). Destacan, por ejemplo, reconstrucciones de perfiles históricos, análisis de impactos, análisis futuros, de vulnerabilidad, participativos, entrevistas, y modelización basada en agentes. Sin embargo, el método más utilizado es la cartografía y análisis espacial (de Vos et al., 2019), que permite identificar, delimitar y caracterizar SSE sin partir de asunciones previas acerca de su distribución espacial (Martín-López et al., 2017; Vallejos et al., 2020). Así, los estudios de cartografía se utilizan para explorar la diversidad de SSE desde la escala local hasta la global. En general, la acumulación de conocimiento obtenido a partir de investigación socio-ecológica basada en el lugar es clave para entender las dinámicas de los SSE a través de contextos y escalas, lo que resulta fundamental para abordar los desafíos de sostenibilidad global, así como para seguir desarrollando marcos conceptuales y teorías sobre SSE (Balvanera et al., 2017a; Martín-López et al., 2020).

El progreso de la investigación socio-ecológica ha propiciado que el concepto de SSE contribuya cada vez más a la toma de decisiones y a la formulación de políticas (Martín-López et al., 2020). Existen varios marcos e iniciativas políticas globales que lo integran. Un ejemplo reciente es la creación de la Agenda 2030 para el Desarrollo Sostenible, adoptada por los Estados Miembros de las Naciones Unidas en 2015, y que define 17 Objetivos de Desarrollo Sostenible para combatir la pobreza y asegurar el bienestar humano dentro de los límites planetarios (Naciones Unidas, 2015). Otro ejemplo es el Panel Intergubernamental sobre Biodiversidad y Servicios de los Ecosistemas (IPBES), creado en 2012 y abierto a todos los miembros de las Naciones Unidas. Su principal objetivo es "reforzar la interfaz ciencia-política para la biodiversidad y los servicios de los ecosistemas para la conservación y uso sostenible de la biodiversidad, bienestar humano a largo plazo y desarrollo sostenible" (Díaz et al., 2015). También destaca la iniciativa Future Earth (Rockström, 2016), que aspira a ser el mayor y más ambicioso programa de investigación internacional jamás desarrollado. Nació con el objetivo de integrar a las ciencias naturales y sociales, para avanzar hacia una ciencia del cambio global orientada a dar soluciones a los retos que plantea el Antropoceno, involucrando a los gobiernos, la sociedad civil y el sector privado. Como parte de esta iniciativa, PECS (Programme on Ecosystem Change and Society) es un programa de investigación internacional que pone el foco en los SSE (Carpenter et al., 2012; Norström et al., 2017). Para que el concepto de SSE continúe permeando en la formulación de políticas, tanto a nivel internacional como nacional y local, es fundamental abordar los siguientes desafíos que obstaculizan el avance de la investigación sobre SSE.

Desafíos para el avance de la investigación en sistemas socio-ecológicos

El estudio de los SSE es un campo de investigación emergente. A lo largo de sus 20 años de recorrido, la investigación socio-ecológica se ha nutrido conceptual y metodológicamente tanto de las ciencias naturales como sociales. Por ello, aún no existe un marco metodológico propio consolidado y el concepto de SSE continúa evolucionando (Herrero-Jáuregui et al., 2018). Aunque la diversidad de análisis y enfoques aplicados ha permitido progresar en el conocimiento de los SSE (Colding & Barthel, 2019), el pluralismo conceptual y metodológico está dificultando la síntesis y comparación de datos, lo que constituye uno de los principales desafíos a los que se enfrenta la investigación socio-ecológica en la actualidad (de Vos et al., 2019).

Existen distintas aproximaciones que pueden contribuir a la comparabilidad de los estudios empíricos sobre SSE. Una de ellas es la utilización de marcos conceptuales y listados de referencia de variables como guía o soporte para el desarrollo de las investigaciones (Cox et al., 2020; Ostrom, 2009). El marco de Ostrom (2009) es de los más integradores y con mayor relevancia (Partelow, 2018), pues su estructura jerárquica y la incorporación de un listado de variables ha favorecido un uso amplio y flexible. En su desarrollo han contribuido varios trabajos posteriores (p. ej., Cox et al., 2020; Delgado-Serrano & Ramos, 2015; Frey, 2017; McGinnis & Ostrom, 2014) que incluso han elaborado repositorios de datos abiertos para su puesta en práctica (Cox et al., 2020). Sin embargo, varios estudios han reportado dificultades en la aplicación empírica del marco de Ostrom relacionados con el entendimiento y la estandarización de las variables, y la recolección de los datos (p.ej., Basurto et al., 2013; Cox, 2014; Delgado-Serrano & Ramos, 2015; Dressel et al., 2018; Leslie et al., 2015). Además, su aplicación principal para el diagnóstico de SSE locales (p.ej., pesquerías, bosques, cuencas hidrográficas) (Partelow, 2018) dificulta extrapolar y comparar los resultados obtenidos (Rocha et al., 2020). Solo algunos estudios recientes han aplicado este marco a la identificación y cartografía de la diversidad de SSE a escala regional (Dressel et al., 2018; Rocha et al., 2020), utilizándolo como soporte para estructurar las variables y caracterizar los sistemas identificados. En general, aunque existen varios marcos conceptuales para el estudio de SSE (Binder et al., 2013), su uso en la investigación socio-ecológica basada en el lugar no está generalizado (de Vos et al., 2019).

La definición de arquetipos es otra aproximación que contribuye a generar conocimiento más comparable y generalizable sobre SSE (Oberlack et al., 2019). Los arquetipos identifican patrones recurrentes en las variables y procesos que caracterizan a estos sistemas (p.ej., tipos de interacciones humanos-naturaleza). Son una herramienta fundamental para trabajar con la complejidad de los SSE a un nivel de abstracción intermedio entre los casos específicos y teorías generales, facilitando la transferencia de conocimiento a través de contextos y escalas (Oberlack et al., 2019). Los arquetipos pueden ser identificados tanto de forma inductiva (p.ej., identificando características comunes dentro de un conjunto de casos de estudio) como deductiva (p.ej., a través de la identificación teórica de variables clave que crean un espacio tipológico) (Meyfroidt et al., 2018).

La cartografía espacial de SSE constituye un enfoque fundamental para la identificación inductiva de arquetipos (Sietz et al., 2019). Desde un punto de vista metodológico consiste en aplicar una técnica estadística de agrupamiento para clasificar unidades de estudio en base a su similitud (p. ej., píxeles, municipios, o cualquier otra entidad espacial), a lo largo de extensiones espaciales que pueden abarcar desde la local hasta la global (Rocha et al., 2020). Los SSE identificados a través de esta metodología son, en definitiva, unidades territoriales que comparten características sociales y ecológicas, así como patrones de interacción humanos-naturaleza similares (Vallejos et al., 2020). Los primeros estudios inductivos sobre cartografía de SSE surgieron hace algo más de una década, por lo que aún es una aproximación metodológica en pleno desarrollo con enfoques muy variados. La selección de variables se ha realizado habitualmente de forma deliberada. Algunos estudios utilizaron un número reducido de variables (menos de cinco; Alessa et al., 2008; Ellis & Ramankutty, 2008) mientras otros emplearon bases de datos extensas (más de 20 variables; Václavík et al., 2013). Unos incorporaron datos sociales, ecológicos y de interacción (Vallejos et al., 2020), mientras otros se basaron solo en alguna dimensión concreta como la provisión o demanda de servicios de los ecosistemas (Hamann et al., 2015; Quintas-Soriano et al., 2019; Raudsepp-Hearne et al., 2010). En este sentido, los estudios más recientes enfatizan en la importancia de utilizar bases de datos amplias, y en estructurar las variables seleccionadas en un marco conceptual y listado de referencia de variables (Dressel et al., 2018; Rocha et al., 2020). En cuanto a la técnica para identificar los SSE, unos estudios se basaron en el solapamiento de unidades ecológicas y sociales (Alessa et al., 2008; Castellarini et al., 2014; Martín-López et al., 2017), mientras otros aplicaron técnicas más complejas de agrupamiento estadístico multivariante (Levers et al., 2018; Václavík et al., 2013). Estas técnicas de agrupamiento (tipo análisis clúster) responden mejor a las propiedades emergentes de los SSE que trascienden la mera suma de aspectos sociales y ecológicos (de Vos et al., 2019; Liu et al., 2007b). En cuanto a la extensión espacial de las cartografías, existen ejemplos tanto a escala local (Martín-López et al., 2017) y regional (Levers et al., 2018), como global (Asselen & Verburg, 2012). Todos estos estudios coinciden en que los mapas de SSE son una herramienta para el desarrollo de una planificación territorial integrada y contexto-específica que reconozca los vínculos entre los seres humanos y la naturaleza. Sin embargo, la pluralidad de aproximaciones y métodos podría obstaculizar la obtención de resultados comparables sobre la configuración y dinámica de los SSE (de Vos et al., 2019).

Por otra parte, los enfoques deductivos para la identificación de SSE permiten detectar arquetipos a través de un conjunto teórico de variables clave que describe las relaciones humanos-naturaleza (Meyfroidt et al., 2018). Estos enfoques normalmente proponen clasificaciones de tipos de SSE modelo (p. ej., Cumming et al., 2014; Dorninger et al., 2017; Fischer et al., 2017; Fischer-Kowalski et al., 2014; Hartel et al., 2018), que puede utilizarse como plantillas para diagnosticar configuraciones socio-ecológicas a través de contextos y escalas. Por ejemplo, Sieferle (1997, 2001) (en Fischer-Kowalski et al., 2014) describió diferentes modos de organización socio-ecológica en función del tipo de sociedad y sus impactos en el medio ambiente, distinguiendo entre el modo cazadores y recolectores, el modo agrícola y el modo industrial. Cumming et al. (2014) se basaron en las implicaciones que estos modos de subsistencia tienen en los vínculos entre las personas y los ecosistemas, para diferenciar entre sistemas *green-loop* (i.e. dependientes de servicios de los ecosistemas locales), *red-loop* (i.e. no dependientes de servicios de los ecosistemas locales) y sistemas en transición. Dorninger et al. (2017) emplearon una perspectiva a escala regional para caracterizar el nivel de conexión biofísica humanos-naturaleza en función de variables como la apropiación humana de la producción primaria neta, el uso de insumos minerales para la producción agrícola, las emisiones, la importación y exportación de mercancías de la biomasa. Así, distinguieron entre sistemas no industrializados, moderadamente industrializados, industrializados orientados a la exportación, e industrializados dependientes de la importación. Otro ejemplo es el de Fischer et al. (2017), en el que se analizaron los nexos entre la seguridad alimentaria y la conservación de la biodiversidad para distinguir entre cuatro arquetipos de SSE a nivel de paisaje correspondientes a estados *win-win* (p. ej., agroecología), *win-lose* (agricultura intensiva), *lose-win* (conservación de la biodiversidad), y *lose-lose* (paisajes degradados). Más recientemente, Hartel et al. (2018) definieron cuatro arquetipos de SSE para los territorios de pastoreo europeos en función de sus aspiraciones socioeconómicas (i.e., producción convencional o sostenible) y el capital financiero disponible (i.e., bajo o alto). En general, la principal ventaja de estas clasificaciones deductivas es que facilitan las comparaciones, generalizaciones, y la transferencia de conocimientos entre casos de estudio. Sin embargo, estos arquetipos pueden ser difíciles de encontrar empíricamente (Oberlack et al., 2019), y resultan demasiado generales para capturar el rango completo de situaciones que existen en el mundo real (Fischer et al., 2017). Ello puede obstaculizar la identificación de respuestas políticas y de gestión ajustadas a cada contexto.

Por lo tanto, no existe una única aproximación válida para avanzar en la producción de conocimiento más generalizable en investigación socio-ecológica. En este contexto de pluralismo metodológico, es prioritario seguir investigando en el desarrollo de estas aproximaciones, así como en las posibles sinergias derivadas de su aplicación conjunta.

1.2. Justificación de la investigación de esta tesis doctoral

La investigación socio-ecológica basada en el lugar es un pilar clave para el desarrollo de las ciencias de la sostenibilidad (Balvanera et al., 2017a,b). El pluralismo conceptual y metodológico que caracteriza a la investigación socio-ecológica, típico de un campo de investigación emergente y que aúna perspectivas de diferentes disciplinas, ha favorecido un progreso extraordinario de nuestro conocimiento sobre los SSE (Colding and Barthel, 2019; de Vos et al., 2019). Sin embargo, este pluralismo puede dificultar la síntesis y comparación de los resultados de las investigaciones, y ralentizar el avance del conocimiento en el ámbito de los SSE (Colding and Barthel, 2019; de Vos et al., 2019; Herrero-Jáuregui et al., 2018; Partelow, 2018;). La consolidación conceptual y metodológica es clave para que la investigación socio-ecológica basada en el lugar progrese. Para ello es necesario desarrollar herramientas y aproximaciones que faciliten generar conocimiento más comparable (Magliocca et al., 2018; Meyfroidt et al., 2018), y que ayude a comprender dinámicas socio-ecológicas a través de contextos y escalas.

Los marcos conceptuales y listados de referencia de variables constituyen una herramienta fundamental para el desarrollo de una investigación socio-ecológica basada en el lugar más comparable, que facilite acumular conocimiento sobre la configuración y dinámica de SSE a través de contextos y escalas (Colding & Barthel, 2019; Cox et al., 2020; Partelow, 2018). Hasta la fecha, el marco conceptual y listado de variables desarrollado por Ostrom (McGinnis & Ostrom, 2014; Ostrom, 2009) es la principal contribución en el ámbito de los SSE, pero su uso no está generalizado y son varias las dificultades reportadas para su operacionalización en estudios empíricos (Hinkel et al., 2015; Partelow, 2018). Por otra parte, desde el ámbito de la investigación y la política, existe una creciente necesidad de desarrollar listados de variables esenciales que ayuden a coordinar los protocolos de observación y seguimiento de los distintos componentes del sistema Tierra (Reyers et al., 2017). Por lo tanto, es necesario seguir progresando en el desarrollo de marcos conceptuales y listados de referencia de variables del SSE susceptibles de ser utilizados de forma sistemática en investigación socio-ecológica (Partelow, 2018), y que contribuyan a identificar las variables esenciales de los SSE.

Los estudios de cartografía de SSE desempeñan un papel fundamental en el desarrollo de la investigación socio-ecológica basada en el lugar (de Vos et al., 2019) y en la identificación inductiva de arquetipos de SSE (Oberlack et al., 2019). Los trabajos más recientes evidencian la tendencia al uso de bases de datos cada vez más integradoras, y a estructurar las variables en torno a un marco conceptual del SSE (p. ej., Dressel et al., 2018; Rocha et al., 2020; Vallejos et al., 2020). Sin embargo, hasta ahora la selección de variables para la cartografía de SSE se ha realizado deliberadamente, generalmente condicionada por los objetivos de la investigación y la disponibilidad de datos. Por ello, sería interesante desarrollar enfoques impulsados por datos que permitieran identificar las variables más relevantes para explicar la diversidad de SSE en regiones concretas. Esto permitiría generar conocimiento más objetivo y comparable sobre los factores que más determinan la distribución y dinámica de los SSE a través de contextos y escalas, potenciando la interconexión de conocimiento socio-ecológico basado en el lugar (Václavík et al., 2016). Además, este conocimiento empírico podría ser sistemáticamente acumulado y contribuir a iniciativas para identificar las variables esenciales de los SSE basadas en conocimiento experto.

Por otra parte, dada la pluralidad de enfoques y metodologías desarrolladas a través de los estudios de cartografía de SSE, otro reto reside en mejorar la comparabilidad de los arquetipos de SSE identificados inductivamente en distintas partes del mundo. Si bien, como se ha comentado anteriormente, la comparabilidad mejora mediante el uso de marcos conceptuales y listados de referencia de variables, las características de los SSE identificados suelen ser muy específicas y difíciles de contrastar entre contextos. En este sentido, las clasificaciones deductivas de SSE pueden jugar un papel fundamental. Algunos estudios han definido tipologías teóricas de SSE a partir de la observación de patrones de interacción y dinámicas socio-ecológicas recurrentes en el mundo, y que son potencialmente reconocibles a través de contextos y escalas (p. ej., Cumming et al., 2014, Dorninger et al., 2017). Así, la integración de clasificaciones inductivas y deductivas permitiría vincular tipologías contexto-dependientes con patrones globalmente reconocibles, aunando la posibilidad de generalizar el conocimiento obtenido a la vez que manteniendo la contexto-especificidad. Sin embargo, apenas existen estudios que hayan vinculado ambas perspectivas (Hamann et al., 2015).

1.3. Objetivos de la tesis

El objetivo general de esta tesis es generar avances conceptuales y metodológicos para la operacionalización del concepto de sistema socio-ecológico en investigación empírica que contribuyan al desarrollo de conocimiento más comparable y generalizable a través de distintos contextos y escalas.

Para lograr este objetivo, esta tesis aborda los siguientes objetivos específicos:

1. Desarrollar un listado de referencia de variables priorizadas para la caracterización y seguimiento de sistemas socio-ecológicos, integrando evidencias procedentes de revisión bibliográfica y percepciones de expertos recolectadas mediante talleres y encuestas en línea.
2. Desarrollar una aproximación metodológica basada en datos para la identificación empírica de variables relevantes e independientes para la detección y cartografía inductiva de arquetipos de sistemas socio-ecológicos en un contexto determinado.
3. Desarrollar un enfoque para el análisis anidado de arquetipos que retenga la diversidad regional de sistemas socio-ecológicos, permitiendo a la vez las comparaciones a través de regiones. Para ello avanzamos en la integración de las perspectivas inductiva y deductiva para el análisis de arquetipos en dos aspectos: 1) considerando la diversidad de sistemas socio-ecológicos y sus cambios mediante un procedimiento de identificación espacio-temporal, basado en datos; y 2) vinculando los sistemas socio-ecológicos identificados inductivamente a categorías deductivas más amplias de conectividad humanos-naturaleza.

1.4. Estructura de la tesis

Esta tesis se desarrolla en torno a dos áreas fundamentales para la construcción de conocimiento comparable en investigación socio-ecológica (Fig. 1): 1) la identificación de variables clave para el estudio de los SSE; y 2) la cartografía y caracterización de arquetipos de SSE. Los resultados se estructuran en tres bloques, correspondientes a los tres objetivos específicos anteriores, que contribuyen a estas dos áreas desde perspectivas *top-down* y *bottom-up*. Así, los resultados de las secciones 2.1 y 2.2 proporcionan conocimiento sobre variables clave para el estudio de los SSE desde una perspectiva general (*top-down*) basada en conocimiento experto, y desde una perspectiva contexto-específica (*bottom-up*) basada en datos, respectivamente. Por otra parte, los resultados de las secciones 2.2 y 2.3 proporcionan nuevas aproximaciones metodológicas para la cartografía y caracterización de SSE de forma inductiva (*bottom-up*), basada en datos. Además, la sección 2.3 integra la perspectiva deductiva (*top-down*), vinculando los arquetipos identificados inductivamente a categorías deductivas globalmente reconocibles. En general, el conocimiento generado en esta tesis contribuye a dos grandes desafíos científicos: 1) avanzar en la identificación de variables esenciales para el estudio y seguimiento de SSE; y 2) desarrollar cartografías de SSE útiles para procesos de planificación territorial contexto-específicos, pero también capaces de informar estrategias y políticas más globales.

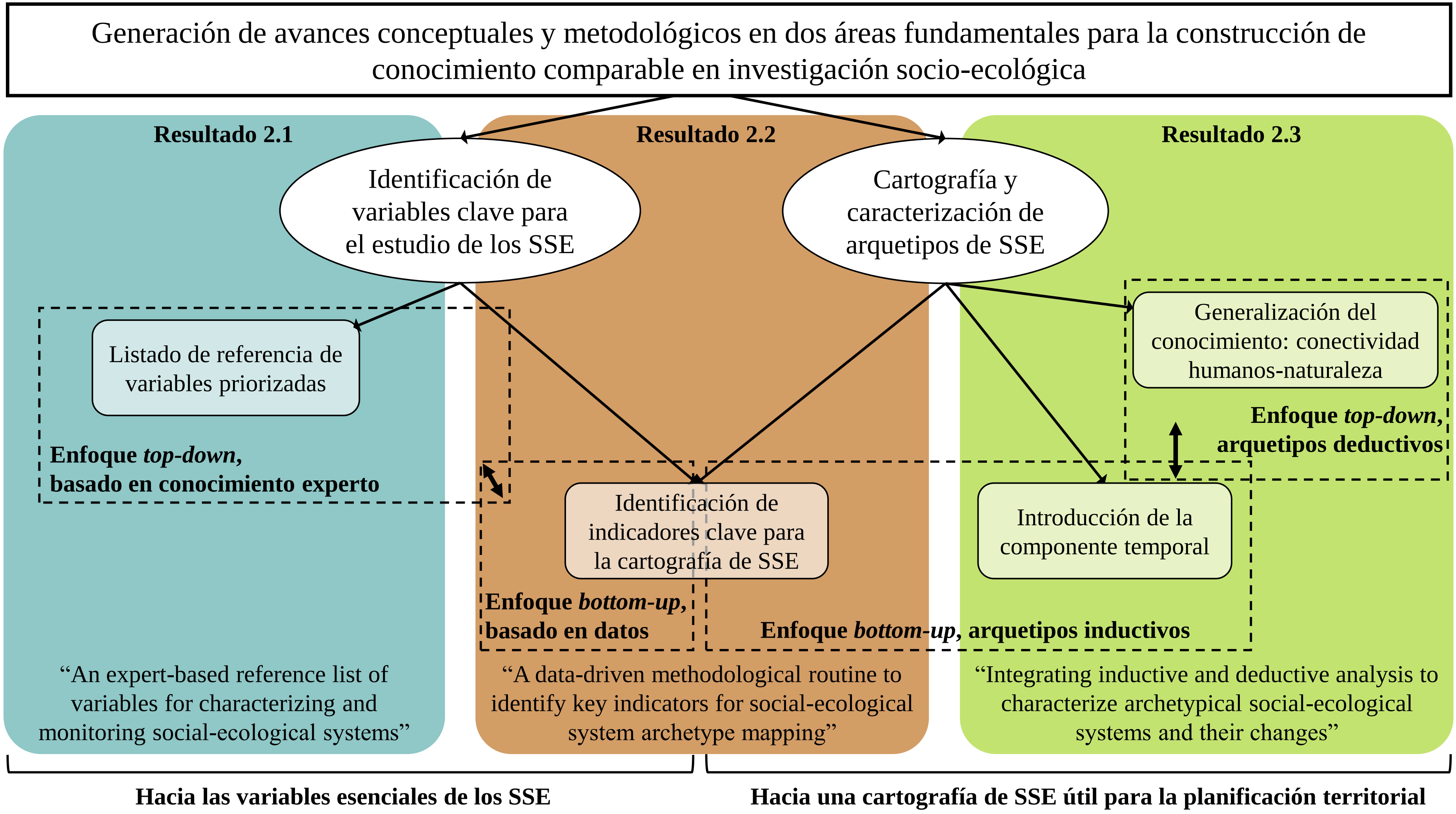
Generación de avances conceptuales y metodológicos en dos áreas fundamentales para la construcción de conocimiento comparable en investigación socio-ecológica
Resultado 2.1
Resultado 2.2
Resultado 2.3
Identificación de variables clave para el estudio de los SSE
Cartografía y caracterización de arquetipos de SSE
Listado de referencia de variables priorizadas
Enfoque *top-down*, basado en conocimiento experto
Identificación de indicadores clave para la cartografía de SSE
Enfoque *bottom-up*, basado en datos
Generalización del conocimiento: conectividad humanos-naturaleza
Enfoque *top-down*, arquetipos deductivos
Introducción de la componente temporal
Enfoque *bottom-up*, arquetipos inductivos
"An expert-based reference list of variables for characterizing and monitoring social-ecological systems"
"A data-driven methodological routine to identify key indicators for social-ecological system archetype mapping"
"Integrating inductive and deductive analysis to characterize archetypical social-ecological systems and their changes"
Hacia las variables esenciales de los SSE
Hacia una cartografía de SSE útil para la planificación territorial

Fig. 1. Estructura de la tesis. A través de las tres principales secciones de resultados de la tesis doctoral (secciones 2.1, 2.2, y 2.3) se han generado avances conceptuales y metodológicos en dos áreas fundamentales (en los óvalos) para la construcción de conocimiento comparable en investigación socio-ecológica. Las contribuciones a estas dos áreas se han realizado desde perspectivas *top-down* y *bottom-up* (cuadros de línea discontinua, conectados por flechas bidireccionales). Nótese que el enfoque desarrollado en la sección 2.2 contribuye a ambas áreas desde una perspectiva *bottom-up*, tanto a la identificación de variables clave, basada en datos, como a la cartografía inductiva de arquetipos de SSE. En la parte inferior de la figura se indican los dos grandes desafíos científicos sobre SSE a los que esta tesis contribuye.

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2. RESULTADOS

2.1. An expert-based reference list of variables for characterizing and monitoring social-ecological systems

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ABSTRACT

The social-ecological system (SES) approach is fundamental for addressing global change challenges and to developing sustainability science. Over the last two decades, much progress has been made in translating this approach from theory to practice, although the knowledge generated is still sparse and difficult to compare. To better understand how SESs function across time, space, and scales, coordinated, long-term SES research and monitoring strategies under a common analytical framework are needed. For this purpose, the collection of standard datasets is a cornerstone, but we are still far from identifying and agreeing on the common core set of variables that should be used. In this study, based on literature reviews, expert workshops, and researcher perceptions collected through online surveys, we developed a reference list of 60 variables for the characterization and monitoring of SESs. The variables were embedded in a conceptual framework structured in 13 dimensions that were distributed throughout the three main components of the SES: the social system, the ecological system, and the interactions between them. In addition, the variables were prioritized according to relevance and consensus criteria identified in the survey responses. Variable relevance was positively correlated with consensus across respondents. This study brings new perspectives to address existing barriers in operationalizing lists of variables in the study of SESs, such as the applicability for place-based research, the capacity to deal with SES complexity, and the feasibility for long-term monitoring of social-ecological dynamics. This study may constitute a preliminary step to identifying essential variables for SESs. It will contribute toward promoting the systematic collection of data around most meaningful aspects of the SESs and to enhancing comparability across place-based research and long-term monitoring of complex SESs, and therefore, the production of generalizable knowledge.

Keywords: coupled human and natural systems; essential social-ecological variables; essential variables; long-term social-ecological research; LTSER; place-based social-ecological research; social-ecological dimensions; social-ecological interactions; social-ecological monitoring; social-ecological system framework; social-ecological system functioning

INTRODUCTION

The social-ecological system (SES) approach arose to formally recognize that human and natural systems are intertwined and interact across nested spatial and temporal scales (Berkes et al., 2000; Chapin et al., 2009). Currently, the SES approach is widely acknowledged as crucial for addressing global change challenges (Carpenter et al., 2009; Liu et al., 2007; Resilience Alliance, 2007) and as a basis for the development of sustainability science (Leslie et al., 2015; Ostrom, 2009). It provides new opportunities to understand and manage critical feedbacks between nature and society, which could lead to better ecosystem health, human well-being and social equity in the distribution of benefits provided by nature (Collins et al., 2011). However, the complex nature of SESs (Levin et al., 2013) and their heterogeneity across the world challenge place-based social-ecological research (Maass et al., 2016; Norström et al., 2017) and the production of generalizable knowledge from these studies.

Over the past two decades, there has been evident progress in moving the SES approach from theory to practice. First, theoretical studies have defined the general characteristics of SESs, explaining their complexity, dynamics, and emergent properties (e.g., Berkes et al., 2003; Chapin et al., 2009; Holling, 2001; Liu et al., 2007). Second, conceptual frameworks were developed to operationalize the SES concept for place-based research (e.g., Chapin et al., 2006; Ostrom, 2009; Redman et al., 2004; Scholz & Binder, 2004). Such frameworks have provided lists of variables and components/dimensions of the SES, including the assumed structural relations between these building blocks, usually supported by a graphical representation (Meyfroidt et al., 2018). Third, the most recent empirical studies have dealt with place-based research through the development of mapping approaches that characterize the diversity of SESs at different spatial scales (e.g., Hamann et al., 2015; Martín-López et al., 2017; Václavík et al., 2013) or that analyze specific types of SESs at the local scale, e.g., such as fisheries, estuaries, and forest systems (Delgado-Serrano & Ramos, 2015; Leslie et al., 2015). Although these empirical studies have provided valuable knowledge on SESs in diverse contexts, it is still difficult to compare and extract general insights from them on how SESs perform over time and across spatial scales (Magliocca et al., 2018; Václavík et al., 2016).

Long-term monitoring provides a fundamental basis for understanding the spatiotemporal dynamics of SESs. This has been made explicit in some global research networks, such as the International Long-Term Ecological Research Network (ILTER) and the Program on

Ecosystem Change and Society (PECS; Holzer et al., 2018). ILTER includes long-term social-ecological research (LTSER) platforms based on the conceptual model of the SES (Collins et al., 2011). These networks constitute infrastructures for inter- and transdisciplinary research and data collection that aim to produce knowledge for addressing the complex environmental challenges that emerge from nature-society interactions and to guide sustainability policies (Dick et al., 2018; Mirtl et al., 2018). The main goal of PECS research is the integration of place-based and long-term social-ecological knowledge generated from case studies across the world to better understand social-ecological dynamics (Balvanera et al., 2017; Carpenter et al., 2012; Norström et al., 2017). In addition, the World Network of UNESCO Biosphere Reserves introduced the social-ecological approach into protected area management, as well as the need to monitor changes in the biosphere resulting from human-nature interactions (Holzer et al., 2018). Despite the promising advances in long-term social-ecological monitoring by these networks, one persistent challenge is the harmonization of monitoring protocols to promote cross-site comparability. This would foster more effective interoperability (Vargas et al., 2017) and knowledge generalization from locally driven research initiatives to broader contexts (Dick et al., 2018; Magliocca et al., 2018).

The systematic collection of standard datasets is the cornerstone for enhancing our ability to study the spatial patterns of SESs and their trajectories over time (Holzer et al., 2018). These datasets should be based on a common core set of variables that contribute to fostering a more comprehensive and comparable characterization and monitoring of SESs (Frey, 2017; Ostrom, 2009). Only a few theoretical studies have dealt with the identification of such common lists of key variables. In this sense, Ostrom (2009) set the most important approach by proposing a list of variables, which were organized in a multilevel nested framework, to understand the sustainability of SESs. Subsequent studies have further developed this list to make it more operational for the empirical study of SESs (e.g., Delgado-Serrano & Ramos, 2015; Frey, 2017; McGinnis & Ostrom, 2014). However, the use of Ostrom’s variables in place-based social-ecological research is challenged because of some limitations. For instance, some studies on specific SESs at local scales have reported difficulties in understanding and standardizing the variables and collecting the data (e.g., Basurto et al., 2013; Cox, 2014; Delgado-Serrano & Ramos, 2015; Leslie et al., 2015). Likely because of these constraints, only a few studies have used this approach for the spatially explicit mapping of SESs (Dressel et al., 2018; Rocha et al., 2020). To overcome these barriers to operationalization, a standard list of variables should be useful in dealing with the diversity of social-ecological contexts (Frey, 2017; McGinnis & Ostrom, 2014), the complex nature of SESs, and the availability of data (Rocha et al., 2020). Finding a set of variables that meets these requirements will enable the collection of datasets worldwide to enhance place-based research on complex SESs as well as the observation and tracking of long-term trends, encouraging cross-system comparisons.

A promising initiative contributing to the development of core lists of variables to make monitoring of the Earth system comparable across sites is the identification of essential variables (EVs). EVs constitute the minimum set of critical measurements for the study, report, and management of a system and its changes (Guerra et al., 2019; Reyers et al., 2017). Major steps have been taken in the fields of biodiversity (Pereira et al., 2013), climate (Bojinski et al., 2014), and oceans (Constable et al., 2016). However, in transdisciplinary fields, only guidelines have been suggested thus far to identify EVs. Reyers et al. (2017) proposed criteria for the selection of EVs that link socioeconomic and environmental concerns for monitoring sustainable development goals. Guerra et al. (2019) defined a framework for identifying EVs that characterize human-nature dynamics in the context of conservation, and Balvanera et al. (2016) developed a pathway for identifying essential ecosystem service variables. Hence, a widespread consensus on a comprehensive list of EVs for SES monitoring is still lacking, although recent studies have provided valuable insights for identifying relevant variables. For instance, Frey (2017) suggested that in addition to SES sustainability, variables could also inform on other outcomes, such as resilience, social equity, or economic efficiency. Holzer et al. (2018) proposed that indicators collected across LTSER platforms might include qualitative social, political, and economic variables, e.g., sense of place, property ownership, or governance structures, to understand trends in quantitative variables, e.g., population density, ecosystem services, or biodiversity. Additionally, within the LTSER context, Dick et al. (2018) highlighted the importance of collecting social and biophysical data for addressing complex challenges that emerge from nature-society interactions, e.g., climate change, biodiversity loss, or environmental hazards. Additional studies that have developed spatially explicit maps of SESs provide multiple examples of relevant variables from which it is feasible to collect data to characterize SES dynamics (e.g., Alessa et al., 2008; Castellarini et al., 2014; Ellis & Ramankutty, 2008; Hamann et al., 2015; Martín-López et al., 2017; Václavík et al., 2013; Vallejos et al., 2020).

In summary, it is crucial to advance toward an established list of relevant and feasible variables for characterizing and monitoring SESs that can be used in science, policy, and management. Developing such a list could foster a long-term coordinated social-ecological monitoring network, allowing the intercomparability of place-based social-ecological research (Balvanera et al., 2017; Carpenter et al., 2012; Collins et al., 2011; Redman et al., 2004) and strengthening the production of generalizable knowledge on SESs across different regions of the world (Frey, 2017). To our knowledge, the few integrative lists of SES variables have been built only from Ostrom's (2009) approach, and difficulties have been sometimes reported for their operationalization in empirical research (Delgado-Serrano & Ramos, 2015). To progress in the development of a core set of integrative variables, it is important to provide new insights into the fundamental traits to characterize the functioning of SESs, i.e., how the system performs (Jax, 2010). For this purpose, it is necessary to compile the variables used in previous studies and to incorporate the assessments of experts working in inter- and transdisciplinary fields (Redman et al., 2004). In this study, we aimed to develop a reference list of prioritized variables for characterizing and monitoring SESs. We provide evidence about the potential most relevant variables based on a comprehensive literature review, an iterative process driven by expert workshops, and researcher perceptions collected through online surveys.

METHODS

Developing a comprehensive list of social-ecological system variables

The list of variables for characterizing and monitoring SESs was developed in four steps (Fig. 1). First, we performed a literature review to search for candidate variables. We also identified candidate conceptual frameworks to structure the list of variables and to depict the relationships among them. We searched Scopus for journal articles and book chapters with the following terms in their titles, keywords, or abstracts: "soci*-ecological system*" and ("map*" or "framework"). Then, we followed a "snowballing" approach (see van Oudenhoven et al., 2018) to identify additional papers that explicitly developed SES maps, SES conceptual frameworks, or were pivotal for understanding SES functioning (Appendix 1A). From this search, we registered all variables and conceptual frameworks that were empirically used or theoretically introduced to characterize SESs. Second, we organized an initial workshop (November 2015) with experts on Earth system dynamics (carbon, water, energy, nutrient cycling) and sustainability science (ecosystem services, transdisciplinarity, translational ecology; see participants in Appendix 1B) to develop a preliminary list of variables structured under an integrative conceptual framework. Experts analyzed the candidate variables and selected the most suitable framework. The variables were classified into a nested scheme of three SES components, and there were multiple dimensions within these components. Third, to complete the list of variables and to validate the structure of the dimensions and components, we conducted a preliminary online survey targeted at researchers with experience in SES science (August-December 2016; see acknowledgments). The survey (Appendix 1C) introduced the list of variables classified into the dimensions and components and asked respondents to score each variable from 0 to 5 according to its relevance for characterizing and monitoring SESs. Scientists were also encouraged to suggest the addition or deletion of variables and to provide any other comments. These scores, suggestions, and comments were analyzed during a second scientific workshop (January 2017; see participants in Appendix 1B) to improve the set of variables and dimensions. We then launched a final online survey (January-May 2017; Appendix 1D) that was distributed to a new group of researchers with similar expertise in SES science (see acknowledgments). As in the preliminary survey, they were asked to score each variable from 0 to 5 and to provide comments and suggestions.

Prioritization of social-ecological variables

To prioritize the variables from the improved list, we conducted a “relevance vs. consensus” analysis using the scores from the final survey (Fig. 1) on the importance perceived by experts for each variable for characterizing and monitoring SESs. The relevance was evaluated as the mean of the scores assigned by the experts to each variable. The consensus was estimated as the difference between the maximum standard deviation of the scores found throughout the 149 variables and the standard deviation of the score for each variable (low differences indicated low consensus and high differences, high consensus). Then, the variables were separately ranked according to their percentile for relevance and consensus and grouped into five categories (four levels of priority and one nonpriority). Priority level 1 (top priority) included variables with relevance and consensus above the 90th percentile; level 2 included variables between the 75th and 90th percentiles; level 3 included variables with relevance above the 75th percentile but consensus between the 50th and 75th percentiles and vice versa; and finally, level 4 included variables with relevance and consensus between the 50th and 75th percentiles. The nonpriority category included variables with relevance and consensus below the 50th percentile. Finally, to assess potential biases and gaps in the list of variables, we analyzed the additional suggestions and comments provided by researchers in both surveys (Fig. 1). This analysis was performed by annotating key words and organizing them through generalization in a conceptual map. We identified recurrent key words (addressed five or more times by respondents) as “featured topics.”

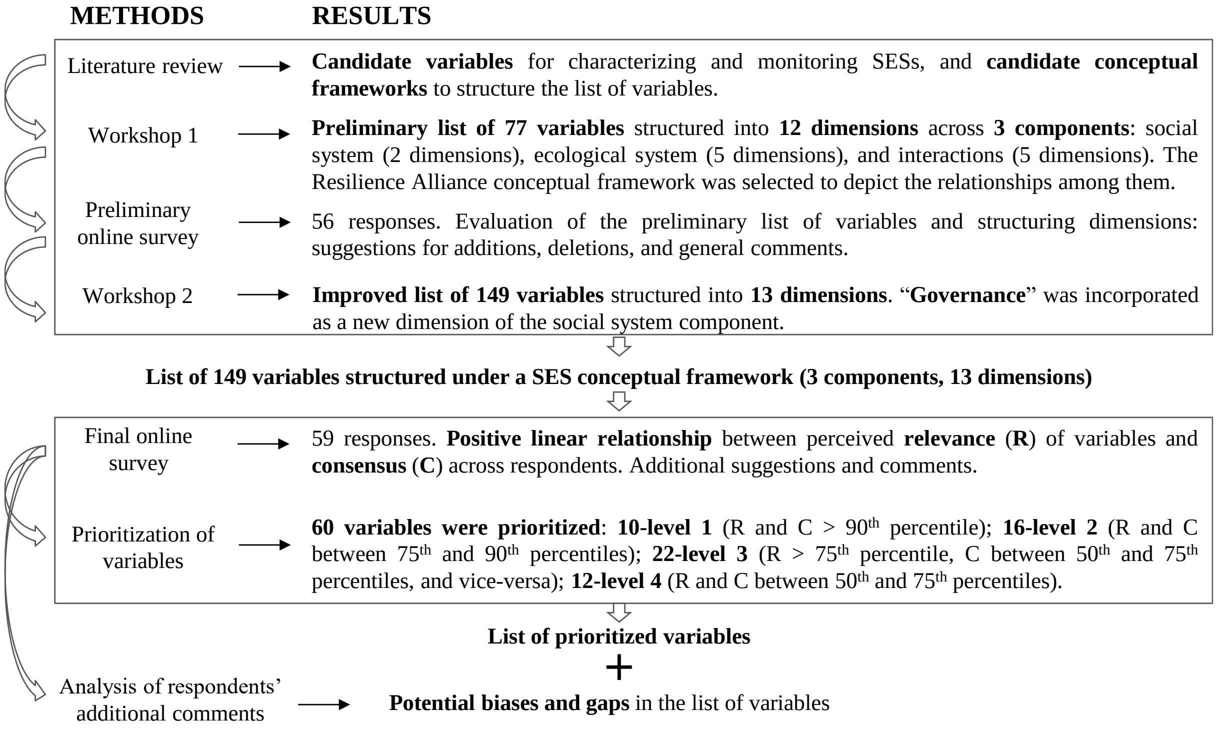

Fig. 1. Workflow. The main methodological steps are identified on the left, and their respective results are on the right. The boxes group together the methodological steps to indicate the two main stages of this study: (1) the development of a list of variables structured under a social-ecological system (SES) conceptual framework and (2) the prioritization of the list of variables.

RESULTS

Variables and dimensions to guide the characterization and monitoring of SESs

We developed a list of 149 variables structured in 13 dimensions within the three components of the SESs: the social system, the ecological system, and their interactions (Appendix 1E, Table E1). We selected the Resilience Alliance conceptual framework (Resilience Alliance, 2007) in the first workshop as the most pragmatic and illustrative framework to depict the structural relations among the dimensions and to guide more coordinated SES characterization and monitoring (Fig. 2). In the social system, three dimensions (human population dynamics, well-being and development, and governance) containing 36 variables were identified. In the ecological system, five dimensions (organic carbon dynamics, water dynamics, nutrient cycling, surface energy balance, and disturbance regime) containing 51 variables were identified. In the interactions between nature and people, five dimensions (ecosystem service supply, ecosystem disservice supply, ecosystem service demand, human actions on the environment, and social-ecological coupling) containing 62 variables were identified. The featured topics derived from the researchers' comments in the preliminary online survey that guided the development of the list of variables and dimensions are shown in Appendix 1F, Fig. F1, as well as in the conceptual map in Appendix 1G.

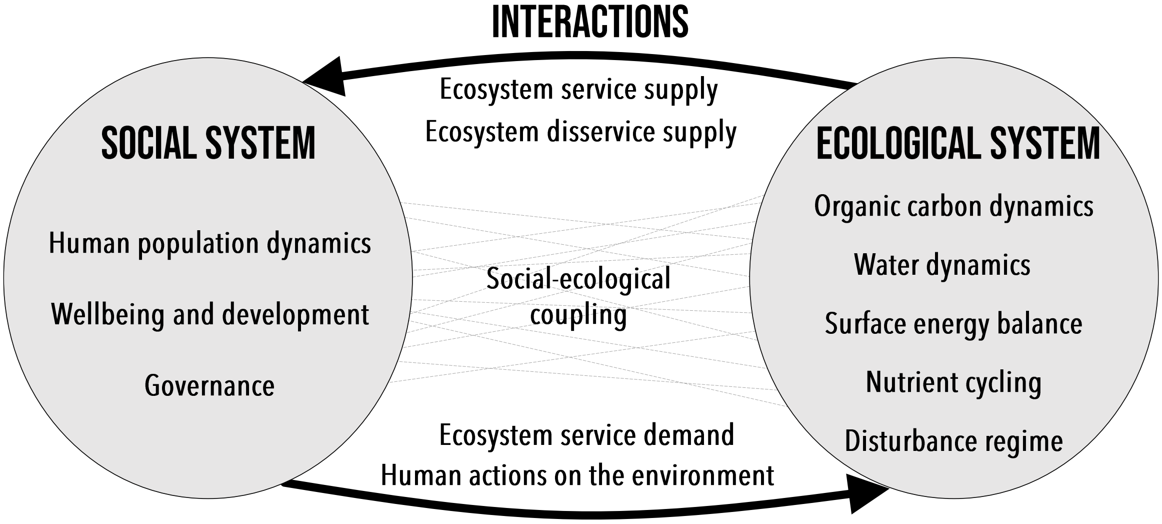

Fig. 2. Conceptual framework to guide the characterization and monitoring of social-ecological systems (SESs). The framework is structured in three components (social system, ecological system, and interactions between them) and 13 dimensions of SES functioning (modified from Resilience Alliance, 2007).

Prioritization of social-ecological variables based on scientist scoring

The analysis of the final survey revealed a significant positive linear relationship (n = 149; r = 0.82; p-value < 0.001) between the average relevance for characterizing and monitoring SESs obtained for each variable and the consensus observed across respondents (Fig. 3). A positive slope lower than one (m = 0.33; p-value < 0.001; root-mean-square error = 0.12) indicated that relevance increased faster than consensus. By applying the prioritization thresholds, 60 variables were considered relevant because they were included at one of the four priority levels (Table 1). Ten variables were included under priority level 1 (highest priority), representing the dimensions of nutrient cycling, disturbance regime (ecological system component), ecosystem service supply, human actions on the environment, and social-ecological coupling (interaction component). Sixteen variables were considered at priority level 2, adding new dimensions such as well-being and development, governance (social system), water dynamics (ecological system), and ecosystem service demand (interaction component). Twenty-two variables constituted priority level 3, incorporating the dimensions human population dynamics (social system), organic carbon dynamics, and surface energy balance (ecological system). Finally, level 4 (lowest priority) added 12 variables, two of them belonging to the dimension of ecosystem disservice supply (interaction component). Thus, the prioritized variables represented all 13 dimensions proposed to characterize SES functioning, though we found it remarkable that no variables in the social system component reached priority level 1, reaching level 2 at the highest. Overall, 25% of the variables assessed for the social system were prioritized, 24% in the ecological system, and 48% for the interaction component. To explore in detail the relevance and consensus obtained for each variable, see Fig. F2 to F14 in Appendix 1F, and Appendix 1H.

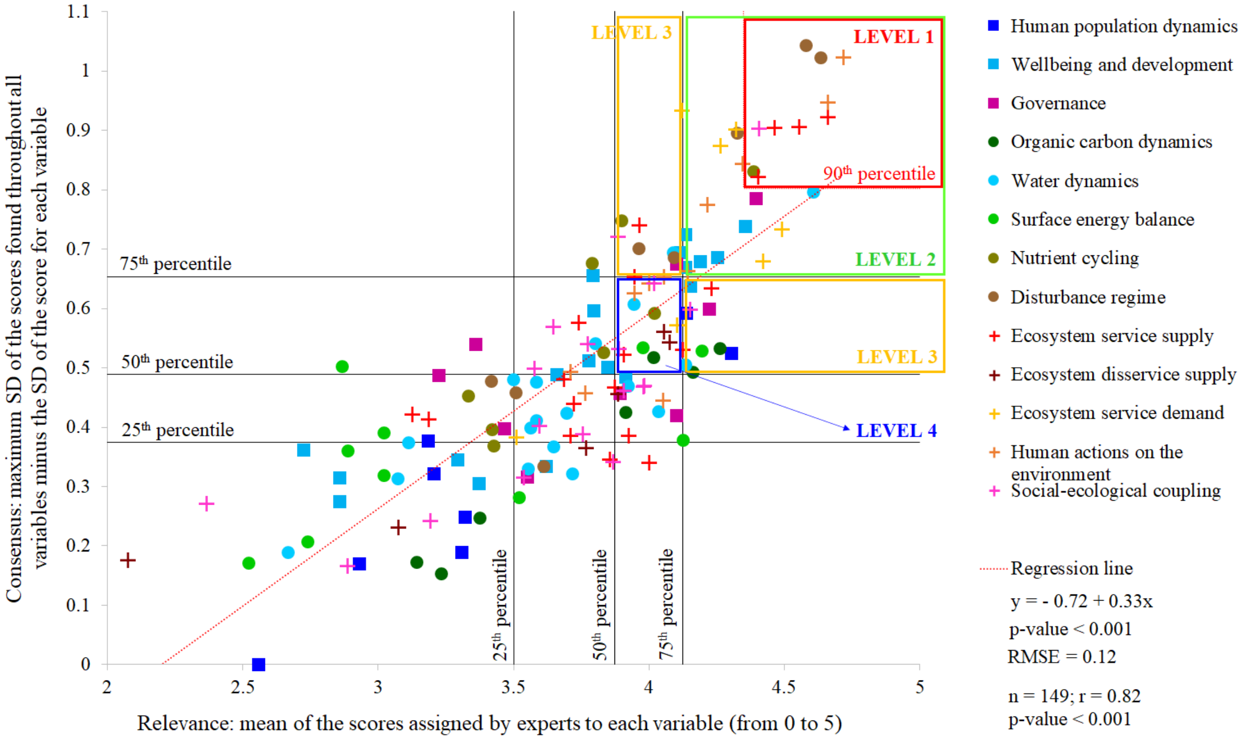

Fig. 3. Relevance and consensus obtained by variables for characterizing and monitoring social-ecological systems (SESs) in the final survey. Relevance was evaluated as the mean of the scores assigned by experts to each variable. The consensus was estimated as the difference between the maximum standard deviation of the scores found throughout the 149 variables and the standard deviation of the score for each variable (low differences indicated low consensus and high differences, high consensus). Squares, circles, and plus signs identify the variables belonging to the social system, ecological system, and interaction components, respectively. Horizontal and vertical lines represent the 25th, 50th, 75th, and 90th percentiles of relevance and consensus. Boxes over the grid illustrate the clustering of the variables by priority levels. The red box (priority level 1) includes those variables with relevance and consensus above the 90th percentile; the green box (level 2) includes those variables with both values between the 75th and 90th percentiles; the yellow box (level 3) includes those with relevance above the 75th percentile but consensus between the 50th and 75th percentiles and vice versa; and the blue box (level 4) includes variables with relevance and consensus between the 50th and 75th percentiles. At the bottom right of the figure, the equation of the regression line, the significance of the line slope (p-value) and the root-mean-square error (RMSE) are indicated, as are the number of variables (n), the Pearson's correlation coefficient (r), and its significance (p-value).

Table 1. List of prioritized variables for characterizing and monitoring social-ecological systems (SESs). The list is structured into 13 dimensions across the three components of a SES (see Fig. 2). Priority level 1 includes variables with relevance and consensus above the 90th percentile; level 2 includes variables with both values between the 75th and 90th percentile; level 3 contains those variables whose relevance was above the 75th percentile and consensus between the 50th and 75th percentiles and vice versa; and finally, level 4 includes those variables with relevance and consensus between the 50th and 75th percentiles. An extended version of this table including the nonpriority variable category, as well as examples and explanations for the variables, is available in Appendix 1E, Table E2.

Component	Dimension	Priority variables (decreasing priority from 1 to 4)			
		Level 1	Level 2	Level 3	Level 4
Social system	Human population dynamics			• Population density • Population distribution	
	Wellbeing and development		• Access to drinking water • Educational level • Environmental quality • Poverty • Social equity	• Water sanitation • Water scarcity	
	Governance		• Current conflicts	• Corruption level • Political stability	
Ecological system	Organic carbon dynamics			• Net primary productivity • Organic carbon storage	• Ecosystem composition by plant functional type
	Water dynamics		• Precipitation	• Actual evapotranspira tion • Actual water deficit (or excess)	• Soil water infiltration capacity
	Surface energy balance			• Net solar radiation	• Land surface temperature
	Nutrient cycling	• Nitrogen fixation		• Soil phosphorus availability	• Nitrogen deposition

	Disturbance regime	• Drought occurrence • Flood occurrence	• Fire occurrence	• Hurricanes/storms occurrence • Pest outbreaks occurrence	
Interactions	Ecosystem service supply[†1]	• Cropland production (P) • Livestock production (P) • Surface and groundwater sources for drinking (P) • Hydrological cycle and water flow maintenance (R)		• Surface and groundwater sources for nondrinking purposes (P) • Local climate regulation (R) • Pest and disease control (R) • Pollination and seed dispersal (R)	• Chemical conditions maintenance of freshwaters and salt waters (R)
	Ecosystem disservice supply[2]				• Abiotic-economic (e.g., droughts, fires) • Bioeconomic (e.g., biological invasions)
	Ecosystem service demand		• Appropriation of land for agriculture • Energy use level • Water use level • Water use for irrigated crops	• Material use level	• Human appropriation of net primary production (HANPP)
	Human actions on the environment	• Land cover/land use change • Land use intensity	• Eutrophication of water bodies • Land protection • Pollution • Soil erosion	• Anthropogenic water management	• Net CO_2 flux • Territorial connectivity
	Social-ecological coupling	• Local natural capital dependence		• Access to natural and seminatural areas • Biocapacity	• Import/export rates of agricultural products • Renewable energy use

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[†] P = provisioning services; R = regulating services

[1] Haines-Young & Potschin (2013), [2] Shackleton et al. (2016) (see Appendix 1E, Table E2)

Additional comments from the respondents

The analysis of respondents' comments and suggestions in the final survey allowed us to identify 14 featured topics indicating potential biases and gaps in the list of variables (Fig. 4 and Appendix 1G). In the social system, several researchers emphasized the importance of "social equity" and "living conditions" to characterize the well-being and development dimension. In the ecological system, "biodiversity" was the most featured topic, which was considered the foundation for explaining the supply of provisioning, regulating, and cultural ecosystem services. Respondents also argued that the water dynamics dimension should be mainly based on the characterization of the "water balance," with some additional variables concerning water and soil salinity and seasonality. Within the interactions, the importance of measuring the "strength of links between people and nature" was the most addressed topic. Within this scope, other related featured topics were "resource consumption patterns," the "cultural value of nature," "cultural ecosystem service demand," "local ecological knowledge," and the "beneficial human actions on the environment." Other highlighted issues were transversal to the three SES components. Some researchers argued that all "variables should reflect the underlying processes and functions" occurring in SESs, instead of outcomes or symptoms of their functioning. In addition, the need to consider more variables related to "energy fluxes" as indicators of system complexity was also suggested. Finally, researchers also stated that variable relevance might be "context-dependent" and that SES complexity makes it "difficult to assess some variables." An extended version of Fig. 4 with the whole list of topics is available in Appendix 1F, Fig. F15.

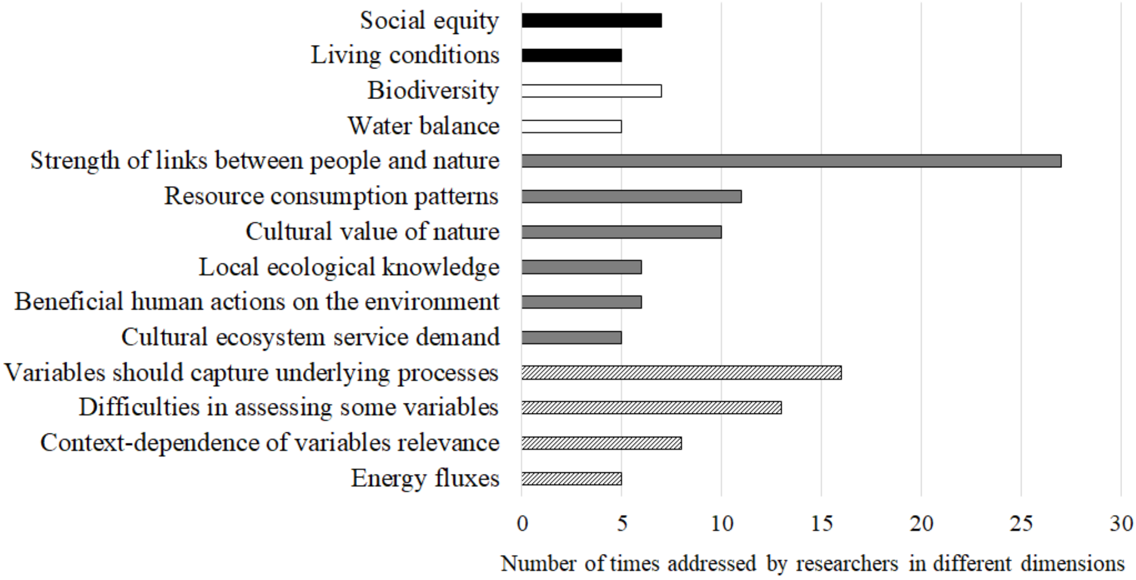

Fig. 4. Featured topics (addressed by five or more respondents in different dimensions) related to potential biases and gaps in the list of variables identified from comments and suggestions in the final survey. Black, white, and gray bars represent the social system, ecological system, and interaction components, respectively, while striped bars reflect issues that are transversal to the whole conceptual framework. (See also these topics in the conceptual map of Appendix 1G).

DISCUSSION

With this study, we contributed to the identification of a common core set of relevant variables for the study and monitoring of SESs by providing a reference list of 60 variables, which were structured in 13 dimensions of SES functioning embedded in the social, ecological, and interaction components of the SES (Fig. 2). The use of such a nested framework contributes to understanding the relationships among variables, aims to maintain the holistic approach in the study of SESs, and promotes transdisciplinary communication by acting as a boundary object (Meyfroidt et al., 2018; Ostrom, 2009; van Oudenhoven et al., 2018). The variables were classified into four levels of priority according to researcher consensus on their relevance (Fig. 3 and Table 1) to facilitate their adaptation to the data availability, context, and sociopolitical needs. The prioritization revealed the crucial role that social-ecological interactions have in characterizing SES complexity (Carpenter et al., 2009; Liu et al., 2007) but also showed that all the dimensions of social-ecological functioning are necessary to disentangle SES dynamics (Table 1). In general, the development of reference lists of variables is an emerging need in sustainability research to foster the collection of structured, long-term, coordinated core datasets across SESs (Frey, 2017; Holzer et al., 2018). This will help to enhance our ability to study SESs over time and across space, enabling cross-system comparisons and the standardization of monitoring protocols.

Insights to address existing barriers in SES research

The list of variables presented in this study offered new perspectives for addressing the main barriers, i.e., applicability to place-based research, representativeness of SES complexity, and feasibility for monitoring, detected in operationalizing existing lists to assess SESs (e.g., Delgado-Serrano & Ramos, 2015; Frey, 2017; McGinnis & Ostrom, 2014; Ostrom, 2009). First, regarding their applicability for place-based research, according to van Oudenhoven et al. (2018), variables not only need to be credible, i.e., scientifically sound based on expert judgment, scientific literature, and a conceptual framework, but also practically feasible for collection. For instance, Ostrom's list of variables, which was conceived to diagnose the sustainability of SESs (Ostrom, 2009), has sometimes been considered too abstract and general to characterize concrete systems (Cox, 2014; Delgado-Serrano & Ramos, 2015; Hinkel et al., 2015; Leslie et al., 2015). To overcome such limitations, we emphasized the selection of variables easily derivable from primary data that have been used in previous research for the spatially explicit mapping of SESs (Appendix 1A and Appendix 1E, Table E3). In addition, the list of variables and the conceptual framework must offer certain flexibility to be adapted to the diversity of contexts and scales of analysis and to data availability (McGinnis & Ostrom, 2014). The Ostrom SES framework presents a hierarchical structure at different levels (tiers), with variables and subvariables that could be adapted depending on the type of SES (Delgado-Serrano & Ramos, 2015) but that lack any guidance on their relevance. In our study, we not only hierarchically structured the variables under the dimensions and components of SESs but also distributed them into priority levels according to their agreed relevance for characterizing SESs. By doing so, we provide guidance for adapting variable selection according to the research context while retaining consistency regarding the relevance and representativeness of variables across SES dimensions.

Second, regarding their representativeness of SES complexity, variables not only need to provide information on the different "pieces" of the system but also must help to understand the linkages among such "pieces" (Ostrom, 2009). To achieve this goal, embedding variables within a nested conceptual framework helps to organize them across components and hierarchical levels while depicting the structural relationships between them (Frey, 2017; McGinnis & Ostrom, 2014; Ostrom, 2009). For instance, Ostrom's SES framework uses an anthropocentric perspective of SESs, where variables that are supposed to focus on the ecological subsystem also have a social origin or reflect the interaction between humans and nature (Binder et al., 2013). However, if most variables make sense only if humans exist, it implies that there exists an unbalanced representation among the social, ecological, and interaction variables, which is acknowledged as a key principle for addressing SES complexity (Liu et al., 2007; Resilience Alliance, 2007; Reyers et al., 2017). Our proposal provides a scheme that categorizes all variables into 13 expert-validated dimensions embedded into the three key components of a SES, i.e., social system, ecological system, and interactions. The variables for characterizing the ecological system followed an “ecocentric” perspective (sensu Binder et al., 2013) and were structured into five dimensions, where the system and its processes were analyzed independently of their links to humans. For the social system, our variables focused on understanding human population dynamics, well-being and development, and governance dimensions without considering ecological processes. Finally, for the interactions between humans and nature, similar to Ostrom (2009), our variables addressed the reciprocity between the social and ecological systems (Binder et al., 2013). However, we suggested a more detailed structure for the variables, which we divided into five dimensions, depending on the type and direction of the interactions: (a) from the ecological to the social system (ecosystem service and disservice supply), (b) from the social to the ecological system (ecosystem service demand and human actions on the environment), and (c) bidirectionally between the social and the ecological system (social-ecological coupling). We recognize that relying on a single framework might be unrealistic, but understanding and generalizing the complexity of SESs requires common hierarchical analytical structures that comprehensively integrate the multiple dimensions and components of SESs (Magliocca et al., 2018; Meyfroidt et al., 2018; Reyers et al., 2017).

Third, regarding the feasibility of the variables for long-term monitoring (van Oudenhoven et al., 2018), our list facilitates SES characterization at the system level, i.e., it focuses on the macrolevels according to Binder et al. (2013) to integrate properties of the SES components as a whole. Aggregated variables at the system level have been clearly more used to characterize, map, and track SESs than variables collected at the individual level, i.e., variables focused on the microlevels according to Binder et al. (2013) to measure properties of the SES individual building blocks, e.g., plant, animal, individual producer, user, or consumer (see examples in Table A5.3). In fact, even those SES mapping strategies based on Ostrom's framework, which combines both system- and individual-level perspectives, i.e., macro- and microlevels according to Binder et al. (2013), have only used system level metrics (e.g., Dressel et al., 2018; Rocha et al., 2020). Several studies show that system-level characterizations can better inform on social-ecological processes from local to global scales (e.g., Levers et al., 2018; Martín-López et al., 2017; Václavík et al., 2013; Vallejos et al., 2020) and could help to overcome current limitations to upscale place-based research for the coproduction of generalizable knowledge on SES (Balvanera et al., 2017).

Potential biases and gaps in the list of variables

The analysis of the researchers' comments revealed potential conceptual biases introduced by the proposed framework during the construction of the list of variables (Fig. 4). In the interaction component, a majority of comments highlighted that sociocultural values and identities might be underrepresented and that the variables addressing the "strength of the links between people and nature" and the "cultural value of nature" could be enhanced, for instance, by incorporating the variable "local ecological knowledge." However, interestingly, cultural ecosystem service variables (following the categories of the Common International Classification of Ecosystem Services, CICES; Haines-Young & Potschin, 2013) were not prioritized by researchers during the survey (Appendix 1E, Table E2 and Appendix 1H). Although these findings may seem contradictory, they align with new insights into the nature's contributions to people (NCP) paradigm (Díaz et al., 2018) and the plurality of values associated with these contributions (Pascual et al., 2017; UNEP, 2015). Under the new NCP paradigm, culture plays a central role in defining all links between people and nature (Díaz et al., 2018). Thus, further lists of SES variables should expand the ecosystem service supply dimension by giving culture and traditional/indigenous knowledge a more transversal role across ecosystem services categories, beyond the independent cultural category of CICES and the Millennium Assessment (MA, 2005). Furthermore, enhancing the characterization of the cultural contexts and identities goes further for the instrumental values of ecosystem services and NCP by incorporating those values that emerge from individual and collective relationships of humans with nature (Chan et al., 2018). To address these "relational values," new variables, such as sense of belonging, responsibility toward nature, or maintenance of traditions (Chan et al., 2016), may be added to the list.

In the ecological system component, the explicit role of biodiversity might also be underrepresented because many comments suggested the addition of more biodiversity variables or of a whole biodiversity dimension within this component. Given the role of biodiversity in SESs as the natural capital that supports social metabolism (Costanza et al., 1997) and the biocentric conservationist tradition (Mace, 2014), we agree that biodiversity could be explicitly named in the framework. However, we initially excluded the structural and compositional biodiversity facets because of their slower response to disturbances compared to functional variables (McNaughton et al., 1989; Milchunas & Lauenroth, 1995). Instead, we focused on the functional aspects of biodiversity at the ecosystem level, such as the candidates to become essential biodiversity variables for the ecosystem function class (e.g., Pereira et al., 2013; Pettorelli et al., 2018).

We are also aware of additional sources of potential methodological biases. On the one hand, the way that the variables were sorted in our framework during the survey could have influenced respondents in assigning priority levels. By displaying the variables sorted into dimensions, we aimed to facilitate the completion of the survey. We are aware that a random display or other sorting could have led to different variable scores. However, this impact may have been low because there was no significant correlation between the priority scores and variable order in the online survey. On the other hand, because the field of expertise of most respondents was sustainability science and ecology (Appendix 1I), the social variables might have received lower scores than expected. Indeed, the social variables never reached the highest priority level (level 1; Appendix 1E, Table E2) despite their importance for human well-being and for explaining the form and intensity of human-nature interactions, e.g., education and population density, respectively (Ellis & Ramankutty, 2008; Hamann et al., 2016). Most inter- and transdisciplinary efforts in social-ecology and sustainability science come from ecology (Holzer et al., 2019; Lowe et al., 2009), but a wide range of perspectives still exist among ecologists for integrating concepts and methods from social science. This disparity of perspectives might be because some researchers consider ecology as a basic science that studies wild nature (where people are only the "ecological audience"), others see it as an instrument for guiding ecosystem and species management (treating people as "ecological agents"), and still others view it as a discipline that considers human societies to be integrated in ecosystems (people as "ecological subjects/objects"; Lowe et al., 2009; Mace, 2014). Indeed, these perceptions of ecology have been evidenced throughout the development and implementation of the long-term social-ecological monitoring network, which mainly originated from ecological monitoring and research. Despite the adoption of a new social-ecological paradigm, the network continues to monitor primarily ecological processes, although it is progressing toward incorporating economic and social data and conducting more germane transdisciplinary research (Angelstam et al., 2019; Dick et al., 2018). In our study, the potential coexistence of these three perceptions among the surveyed researchers could be the basis of the lack of consensus around the most relevant social variables. This highlights the need to strengthen cooperation between natural and social scientists and experts to lead to a truly integrated approach for long-term social-ecological research (Dick et al., 2018). Finally, many scientists have reported difficulties in scoring the variables without considering a specific SES, arguing that variable relevance is context dependent. Although biodiversity, climate, oceans, or sustainable development goal variables may have more evident global perspectives, this is not easily applicable to SES variables given the place-based nature of SES research (Carpenter et al., 2012). All these potential biases should be considered when using our list of variables and formally analyzing them in future assessments.

Toward the definition of essential variables for social-ecological systems

The development of essential variables (EVs) that harmonize global observation networks is a priority for tracking changes and coordinating monitoring efforts (e.g., Bojinski et al., 2014; Constable et al., 2016; Pereira et al., 2013). Despite the call from sustainability science to extend this systemic thinking to areas of interaction between the social and the biophysical domains, building a list of essential social-ecological system variables is still needed (Reyers et al., 2017). The set of dimensions and variables developed here can contribute to creating a common structure to study SESs and to starting to work toward such essential variables. Because the variables and dimensions were based on consensual expert knowledge, their credibility, salience, and feasibility were reaffirmed (van Oudenhoven et al., 2018). In addition, fundamental steps in EV development were followed in the codesign process (Reyers et al., 2017): (1) adoption, through an expert-driven process, of a conceptual model of SESs functioning, representing the social and ecological systems as well as the interactions between them; (2) identification of the broad categories and disaggregated inputs of candidate variables; (3) refining and prioritization of variables based on the consensus on their relevance; and all this by means of (4) an iterative procedure fed by scientific expert knowledge obtained from workshops and online surveys.

However, given the preliminary nature of our exercise, further work is needed to build a global consensus around a set of EVs for the study of SESs. For instance, new surveys should address the potential biases and limitations outlined above, for instance (1) by explicitly considering the role of biodiversity and of relational values about NCP; (2) by having a greater and more balanced number of respondents (particularly the inclusion of social scientists); and (3) by reporting on the most frequently relevant variables in relation to specific place-based social-ecological contexts.

To further develop EVs for SESs, finding common aspects and variables among the existing lists could also help to establish a baseline. Some variables suggested in Ostrom’s (2009) and Frey’s (2017) lists were also relevant in our study. The most common aspects were found for the interaction component. For instance, the harvesting variable on Ostrom’s list was related to human appropriation of net primary production, material use, water use, or energy use on our list. Similarly, pollution patterns on Ostrom’s list were related to eutrophication of water or net CO2 flux on our list; constructed facilities on Ostrom’s list and accessibility on Frey’s list were related to territorial connectivity, access to natural areas, or anthropogenic water management on our list; and importance of resources on Ostrom’s list and dependency on resources on Frey’s list with dependence on local natural capital on our list. In the social system, economic development and socioeconomic attributes (Ostrom, 2009) were associated with poverty, educational level, or social equity variables on our list, and number of actors (Ostrom, 2009) with population density. Similarly, governance-related variables, such as conflicts and political stability, were included on both Ostrom’s list and our list, while Frey (2017) considered conflict management as a crucial aspect for the stability of rule systems and resource use. In the ecological system, Ostrom’s (2009), Frey’s (2017), and our list converged on including climate characteristics and primary productivity or the regeneration rate of resources.

In addition, some of our prioritized variables from the ecological and interaction components of SESs are related to six of the nine major environmental challenges listed in the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). For instance, the monitoring of net solar radiation and net CO2 flux could provide information to assess “climate change” and “atmospheric aerosol loading”; information on biological invasions, pest outbreak occurrence, and ecosystem composition by plant functional types to assess “changes in biosphere integrity”; measuring nitrogen deposition and eutrophication of water to evaluate interferences with “biogeochemical flows”; the appropriation of land for agriculture and land use intensity for “land-system change”; and finally, water use level and water use for irrigated crops to assess “freshwater use.”

From a general perspective, additional steps should be given to foster the institutionalization of the development and implementation of essential SES variables (see Bojinski et al., 2014; Constable et al., 2016; Pereira et al., 2013; Reyers et al., 2017). As a first step, the compliance of the variables with the criteria to be considered essential should be thoroughly checked, for instance, to be (i) state variables, sensitive for long-term monitoring of changes; (ii) representative for the system level, between primary observations and indicators; (iii) flexible to adapt to multiple monitoring programs; and (iv) feasible to observe and derive and to be scaled to meet local, regional or subglobal needs. Second, consensus should be built and coordinated to align the development of the variable list with research and policy needs by setting an open platform for scientist, policy maker, and stakeholder cooperation. Third, the learning loop should be optimized to refine and stabilize the list of EVs by establishing a transparent process with specific targets and time lines to plan the development of the list and track the updates. Finally, to increase the global efficiency of Earth monitoring systems, the interconnection of the EVs that may emerge from our list with other sets of EVs (for biodiversity, climate, oceans, etc.) should be coordinated.

CONCLUSIONS

The development of reference lists of variables is an emerging need in sustainability research to foster the systematic collection of comprehensive and coordinated datasets of SESs and to enhance our ability to study SESs across time and space. These lists of variables structured under a conceptual framework provide a common language that facilitates comparisons and the generalization of knowledge from empirical studies. Although the development of such lists in specific fields of Earth systems (climate, biodiversity, oceans) has progressed significantly in recent years, integrative approaches for SESs are still scarce. With this study, we contributed to the identification of a common core set of variables for the characterization and monitoring of SESs. Our 60-variable list gathered relevant traits and processes of the SES from scientific literature reviews and expert knowledge. This list was embedded in a framework of 13 dimensions across the three key components of the SES (social system, ecological system, and the interactions between them) to help maintain an integrative approach when working with SESs. In addition, variables were classified into priority levels to provide more flexibility in their application to place-based research. Throughout this process, new insights have arisen that could contribute to overcoming existing barriers in the operationalization of lists of variables in the study of SESs, such as the applicability to place-based research, the capacity to deal with SES complexity, or the feasibility for long-term monitoring of social-ecological dynamics. Our list of variables may constitute a preliminary step in the direction of identifying essential variables for SESs, whose further development will provide an opportunity to boost the long-term social-ecological research network. This could strengthen our capacity to respond to global change challenges, extend systemic thinking to the field of human-nature interactions, and foster sustainability sciences through more efficient operationalization of the social-ecological approach.

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2.2. A data-driven methodological routine to identify key indicators for social-ecological system archetype mapping

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ABSTRACT

The spatial mapping of social-ecological system (SES) archetypes constitutes a fundamental tool to operationalize the SES concept in empirical research. Approaches to detect, map, and characterize SES archetypes have considerably evolved over the last decade towards more integrative perspectives using extensive databases, guided by SES conceptual frameworks and reference lists of variables. However, the selection of specific indicators for SES mapping has generally been deliberate, conditioned by research goals or data availability, but scarcely based on the empirical relevance of the indicators. This has resulted in heterogeneous SES interpretations, which hamper comparison across studies and knowledge generalization. In this study, we propose a data-driven methodological routine based on multivariate statistical analysis to identify the most relevant indicators for mapping and characterizing the diversity of SES archetypes in a particular region. Taking Andalusia (Spain) as a case study, we applied this methodological routine to a wide database of 86 indicators representative of multiple variables and dimensions of social-ecological functioning across the three fundamental components of the SES: the social system, the ecological system and their interactions. Additionally, we assessed how the empirical relevance of these indicators contributes to previous expert and empirical knowledge on key variables for characterizing SESs. We identified 29 key indicators that allowed us to map and characterize 15 SES archetypes, representative of natural, mosaic, agricultural, and urban systems, which uncover contrasting land sharing and land sparing patterns throughout the territory. We also identified points of synergy but also of disagreement between empirical and expert knowledge on the relevance of variables to characterize SESs. For 30.6% of the assessed variables, our results agreed with previous empirical and expert knowledge on variable relevance across scales and contexts (e.g., crop and livestock production, net primary productivity, population density). For 18.4% of the variables, such relevance seemed to be conditioned by the context or the scale (e.g., land protection, educational level), whereas in other 18.4% of cases, we found lack of agreement between empirical and expert knowledge (e.g., economic level, land tenure). For the remaining 32.6%, the lack of expert or empirical knowledge highlighted the need of further assessments to clarify the relevance of such variables. Overall, our data-driven approach can contribute to more objective selection of relevant indicators for SES archetype mapping, which can help to produce comparable and generalizable empirical knowledge on key variables for characterizing SESs across contexts and scales, and might support expert assessments in the identification of essential SES variables.

Keywords: correlation analysis; coupled human and natural systems; essential social-ecological system variables; hierarchical clustering; long term social-ecological research; LTSER; principal component analysis; Random Forest

INTRODUCTION

The ubiquitous presence of humans across the planet has shaped most terrestrial ecosystems (Vitousek et al., 1997). Human societies transform the territory, extract natural resources from the surrounding environment, and release the by-products and waste from their activity. Recent research warns that we have overpassed the limits of change for a safe operating space in critical processes that regulate the Earth system functioning and stability (Rockström et al., 2009; Steffen et al., 2015). Conventional territorial planning, often constrained by strict administrative boundaries, has not provided an effective response to curb this global environmental crisis (Sayer et al., 2013). The lack of integrated territorial management policies has prevailed a strong dichotomy between anthropic versus natural, urban versus rural, protected versus non-protected areas, etc. (Palomo et al., 2014). Additionally, the capacity of technology to satisfy human needs, either by overexploiting available resources or by bringing goods and services from distant places, have fed a feeling of independence from nature in large parts of the developed world (Folke et al., 2011; Liu et al., 2015). Thus, as the direct dependence on local ecosystem services decreases, our psychological ties with nature are also weakening (Cumming et al., 2014). Human societies are inextricably linked to their surrounding environment, thereby considering them apart from nature seems today unreasonable (Berkes et al., 2003; Preiser et al., 2018). This debate has now gained special weight in international political agendas as a result of the covid-19 pandemic, which has evinced the vulnerability of humankind to a weakened biospheric integrity (Settele et al., 2020). In the Anthropocene era, humanity faces the great challenge of reconnecting with nature (Ives et al., 2018). To this end, the development of graphic tools (e.g., maps) can help us to visualise and understand how human and natural systems are intertwined and interact.

The need to incorporate the human influence in the study and management of nature pushed Ecology to include the human dimension into its scope (Herrero-Jáuregui et al., 2018; Lowe et al., 2009). Thus, with the emergence of socio-ecology, the coupling between human and natural systems was formally recognized (Berkes & Folke, 1998), and the social-ecological system (SES) concept became a fundamental basis for the development of sustainability science (Berkes et al., 2003; Fischer et al., 2015; Liu et al., 2007). Over the past two decades, substantial conceptual and methodological advances have been made to operationalize the SES concept in empirical research (Levin et al., 2013; Ostrom, 2009). In this sense, the development of different approaches to detect and map the diversity of SESs over territories has significantly contributed to place-based social-ecological research (de Vos et al., 2019; Oberlack et al., 2019). Such approaches have essentially been based on identifying patches of land where recurring social and ecological patterns and dynamics of human-nature interaction occur (i.e., archetypes of SESs; Rocha et al., 2020). Thus, SES maps are useful to structure and characterize the social-ecological complexity (Vallejos et al., 2020). They can work as templates for decision-makers to develop more sustainable models of territorial management that consider the interdependence between social and ecological systems (Oberlack et al., 2019). Although approaches to detect and map SESs have evolved considerably over the last decade, their conceptual and methodological differences could hinder the obtention of generalizable knowledge on SES dynamics across the globe (de Vos et al., 2019; Magliocca et al., 2018).

Generally, the indicators used in SES mapping have been deliberately selected depending on the research goals or data availability. Whereas the earliest approaches usually used small sets of indicators and identified SESs by overlapping layers of spatial data (e.g., Alessa et al., 2008; Ellis & Ramankutty, 2008), the most recent ones integrate more comprehensive databases through complex statistical techniques (e.g., Dressel et al., 2018; Rocha et al., 2020; Vallejos et al., 2020). This pluralism has resulted in diverse interpretations of SES, although, in essence, all approaches combine ecological, social, and/or human-nature interaction indicators. For instance, anthromes were mapped from indicators of land cover, population density, and land-use (Ellis & Ramankutty, 2008); social-ecological hotspots emerged from overlying net primary production and human-perceived biological value of the landscape (Alessa et al., 2008); and socio-ecoregions, by combining ecoregions and human development index (Castellarini et al., 2014). SESs have also been identified by mapping bundles of ecosystem service supply or demand as an integrated expression of underlying social-ecological dynamics (e.g. Hamann et al., 2015; Queiroz et al., 2015; Quintas-Soriano et al., 2019; Raudsepp-Hearne et al., 2010; Spake et al., 2017). Other studies focused on indicators of land cover and land use intensity to map land-use systems (Asselen & Verburg, 2012; Levers et al., 2018). More comprehensive approaches were applied to map land system archetypes (Václavík et al., 2013) and social-ecological units (Martín-López et al., 2017), which used wider sets of indicators to characterize ecological, social and interaction factors of the SESs. Recently, approaches to map SES archetypes (Dressel et al., 2018; Rocha et al., 2020) and social-ecological functional types (Vallejos et al., 2020) took a step forward by using a supporting conceptual framework and reference list of variables to guide the indicator selection, the structuring of the database and the characterization of SESs, which can contribute to developing more comparable and integrative research (Cox et al., 2020). However, to our knowledge, there are no SES mapping studies that have investigated yet the most relevant set of indicators to characterize the diversity of SESs of a given region.

Knowing which are the most relevant general variables for the study of SESs is a current scientific aim to foster the development of more comparable place-based social-ecological research and harmonized long-term monitoring protocols (Balvanera et al., 2017; Cox et al., 2020; Holzer et al., 2018; Mirtl et al., 2018; Pacheco-Romero et al., 2020). In recent years, significant research endeavours are being targeted to build reference lists of variables for characterizing Earth system components. Thus, sets of ‘essential variables’ have been identified for the study of biodiversity, climate or the oceans (Bojinski et al. 2014; Constable et al. 2016; Pereira et al. 2013), which is fostering global strategies for coordinated monitoring and data collection and sharing. However, to characterize SESs, only first steps have been taken towards identifying essential variables, and the generated knowledge is still sparse. For instance, some studies have built reference lists of variables for characterizing and monitoring SESs (Cox et al., 2020; Frey, 2017; McGinnis and Ostrom, 2014; Ostrom et al., 2009; Pacheco-Romero et al., 2020). In addition, some initiatives are developing frameworks to identify essential variables for sustainable development goals (Lehmann et al., 2020; Reyers et al., 2017), for conservation management in natural protected areas (Guerra et al., 2019), or for measuring and monitoring ecosystem services (Balvanera et al., 2016). To advance in the identification of essential variables for SESs, producing comparable knowledge through place-based social-ecological research is fundamental. In this sense, the potential of SES mapping could be fostered through new approaches that systematically identify the most relevant indicators for characterizing the diversity of SESs across territories.

In this study, we aimed to develop a data-driven approach to identify the most relevant indicators to map SES archetypes, which we define as unique combinations of social, ecological, and human-nature interaction factors, with patterns that appear repeatedly throughout the territory (Oberlack et al., 2019; Rocha et al., 2020; Václavík et al., 2013). Here we focused on indicators, as the specific measurements used to characterize more general variables. Thus, our goal was to enhance objectivity in the indicator selection process by a more standardized and repeatable method that facilitates the comparability and knowledge generalization of SES mapping studies. Specifically, we proposed a data-driven methodological routine to detect and map SESs by identifying the most statistically meaningful indicators to capture the social-ecological diversity. We also used a reference list of variables and a conceptual framework (Pacheco-Romero et al., 2020) to structure the indicator's database and characterize the identified SESs. We used the pilot case study of Andalusia (southern Spain) to illustrate the common process of responding the following three questions when mapping SES archetypes:

1) What are the most relevant indicators to identify and characterize the diversity of SES archetypes?
2) What are the main SES archetypes and the characteristics that define them?
3) What does our data-driven selection of indicators contribute to previous expert and empirical knowledge on key variables for characterizing and mapping SESs?

METHODS

In brief, we first compiled a comprehensive database of multiple indicators representing the main variables and dimensions of SES functioning across its three main components (i.e., social system, ecological system, and interactions). We obtained these indicators at the municipality resolution for Andalusia, which represents an ecologically and culturally diverse region with high availability of social and ecological data. Then, we applied a methodological routine based on multivariate analysis to screen the database and select the most relevant indicators to map and characterize the SES archetypes of this. Finally, we assessed how the empirical relevance of the indicators contributes to previous expert and empirical knowledge on key variables for the study of SESs.

Database development

We developed a database of 86 indicators using open regional databases (Appendix 2A, Table A1). We based on the reference list of variables and conceptual framework for characterizing SESs proposed by Pacheco-Romero et al. (2020) to structure the database. Thus, our indicators were representative of 49 variables across the distinct levels of priority defined in this list (including non-priority variables), and were distributed into 11 dimensions of SES functioning. The 23 indicators that characterized the social system component were descriptive of the human population dynamics, well-being and development, and governance dimensions. For the ecological system component, 14 indicators represented the principal matter and energy fluxes across the carbon dynamics, water dynamics, surface energy balance, and disturbance regime dimensions. Finally, for the interaction component, 49 indicators addressed the reciprocity between the social and ecological systems across the ecosystem service supply dimension, the ecosystem service demand and human actions on the environment dimensions, and the social-ecological (de)coupling dimension (i.e., the strength of links between the social and the ecological system).

Our database consisted of categorical and continuous indicators. We aggregated all indicators at the municipality level (n=778 municipalities) by calculating the spatial mean for continuous indicators and the relative area share of specific classes of interest for categorical indicators. To ensure comparability among municipalities, we calculated relative values (e.g., per unit area, per inhabitant, area share) when needed (Appendix 2A, Table A2).

Identification of key indicators for SES mapping

We developed a multivariate analysis routine to screen the initial database by sequentially eliminating the least relevant and highly correlated indicators (Fig. 1). First, we inspected Pearson's correlations to identify highly correlated indicators. Second, we assessed the relevance of all the indicators by two parallel approaches. On the one hand, we ran principal component analysis (PCA) to inspect the relevance (weights) of all indicators in the eigenvectors of the two first PCA axes, independently of any SES classification. On the other hand, we ran random forest analysis (RF) (Breiman, 2001) by using as independent variables all indicators, and as dependent variable the SES class assigned to each municipality by a hierarchical cluster analysis (Equation 1). The clusters grouped municipalities into 15 SES classes based on Ward's method, which minimizes the total variance within clusters (Ward, 1963), and a less restrictive Manhattan distance to ensure convergence (Rocha et al., 2020). After inspecting different cut-off levels of the cluster dendrogram, we decided this number of clusters based on our knowledge of the study area, and we kept it constant throughout the analysis. From RF run, the Mean Decrease Accuracy (MDA) index of each indicator was used to assess the indicator's importance for identifying SESs. This index represents how the accuracy of the classification of municipalities into the SES clusters decreases if an indicator is eliminated. Thus, the higher the value of the index, the greater the importance of the indicator (Archer & Kimes, 2008; Han et al., 2016). We contrasted both PCA and RF outputs to increase the robustness of our decisions throughout the subsequent indicator screening process. In case of disagreement, we prioritize RF results for being dependent on our specific SES classification. We performed all the analysis in R (R Core Team, 2018).

Equation 1: municipality SES cluster (n=778, i = 1-15) ~ PD_1 + PD_2 + PD_3 + WB_2 + WB_4 + G_5 + G_6 + OCD_2 + WD_1 + SEB_1 + SEB_2 + DR_4 + DR_7 + ESS_1 + ESS_2 + ESS_7 + ESS_9 + ESS_10 + HAE_2 + HAE_3 + HAE_7 + HAE_8 + HAE_11 + HAE_15 + SEC_1 + SEC_2 + SEC_7 + SEC_10 + SEC_13

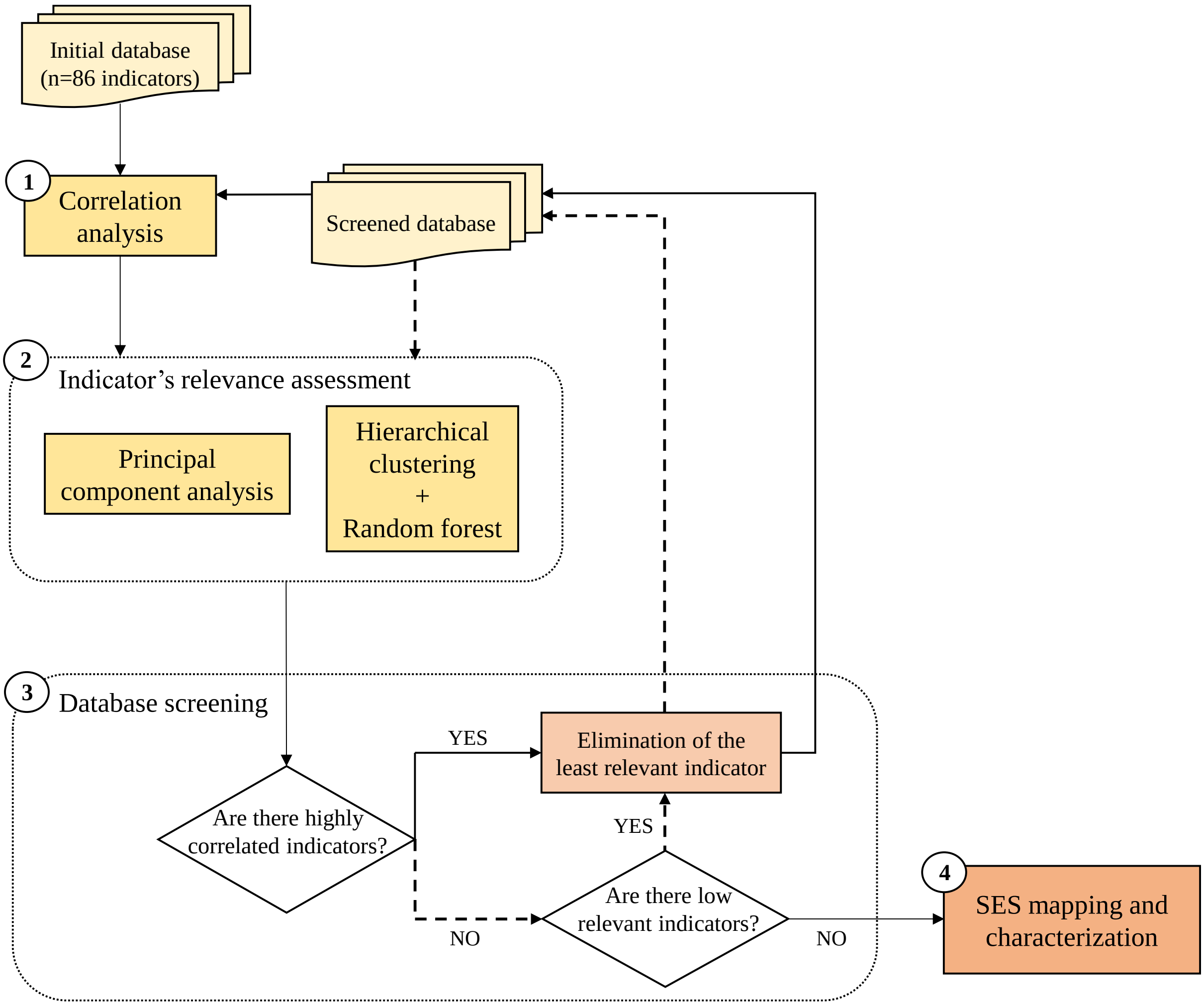


Fig. 1. Multivariate analysis routine to identify the most relevant indicators for social-ecological system mapping: 1) Pearson's correlations to identify highly correlated indicators; 2) assessment of indicator relevance by applying a principal component analysis (independent of the SES clustering) and a random forest (dependent on the SES clustering); 3) sequential screening of the database by discarding the most correlated and least relevant indicators, one at each loop of the routine; 4) mapping and characterization of SESs from the final screened database. Dashed arrows indicate the alternative path when no highly correlated indicators remain in the database.

Third, we screened the database by discarding the most correlated and least relevant indicators, one at each loop of the routine. We eliminated correlated indicators first, discarding those that showed the lowest relevances in the PCA and RF. For our particular case study, we set the threshold for correlation coefficients higher than 0.7, or lower than -0.7. Once correlation was reduced in the database overall, we continued eliminating the least relevant indicators. For our case study, we considered as low relevant indicators those that had a MDA index value below 20. Thus, we halted the screening process when no indicator showed a MDA below this threshold.

Mapping and characterization of social-ecological systems

Fourth, once the database was screened, we mapped the SES cluster memberships for all municipalities from the last hierarchical clustering. To characterize the identified SESs, 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. Based on the impact of indicators in each cluster, our knowledge of the study area, and other regional zonings (e.g., landscape units, ‘comarcas’, biogeographical sectors), we then described, labelled, and classified SESs according to their characteristics and spatial patterns.

Comparing empirical and expert knowledge on the relevance of variables to characterize and map SESs

Finally, we assessed how the empirical relevance of the indicators contributes to previous expert and empirical knowledge on key variables for the study of SESs. For that, we focus on the 49 variables characterized by the 86 indicators used in our analysis (Appendix 2A, Table A1) and assessed: 1) the use of such variables by previous SES mapping studies (in local/regional scales or across scales); 2) their relevance according to expert knowledge; and 3) their relevance for our specific case-study. For point one and two, we based on a previous review on SES mapping studies (Appendix 1E, Table E3) and a reference list of prioritized variables (Appendix 1E, Table E2), respectively, proposed by Pacheco-Romero et al. (2020).

RESULTS

Key indicators for SES mapping

From the initial list of 86 indicators, we identified 29 relevant and independent indicators for mapping the diversity of SES in Andalusia, representing ten of the 11 dimensions of social-ecological functioning (Fig. 2; Appendix 2A, Table A1; Appendix 2B, Fig. B2). In the social and the ecological system components, seven and six indicators were respectively selected, which represented all the seven dimensions of SES functioning. However, in the interaction component, all indicators from the ecosystem service demand dimension were discarded for being highly correlated to other indicators (e.g., cropland area) or for not being useful to discriminate among SESs (e.g., indicators describing water use and energy use variables). Thus, the 16 selected indicators from this component only represented three out of four dimensions.

The 10 most relevant indicators to explain the diversity of the identified SESs included characteristics of the ecological system (mean annual temperature, desertification rate, seasonal coefficient of variation of the enhanced vegetation index, mean annual precipitation, net solar radiation), and of the interaction component (natural surface area, landscape diversity, night sky quality, greenhouse gas emissions in urban waste treatment, cropland productivity). On the other hand, at the bottom of the ranking were some indicators of the social system component (population density, population dispersion, population mean age, mean income and agricultural subsidies) and of the interaction component (livestock production, total greenhouse gas emissions, employments in agriculture, average farm area, CO_2 emissions in goods transport). Overall, ecological system indicators were at the top of the ranking, while social system indicators were at the bottom. For a detailed view of the results of the database screening, see the groups of correlated indicators (Appendix 2B, Fig. B1), and the indicators eliminated throughout the screening process (Appendix 2A, Table A1), both for being the least relevant indicators among the correlated ones, or the least relevant indicators from the database.

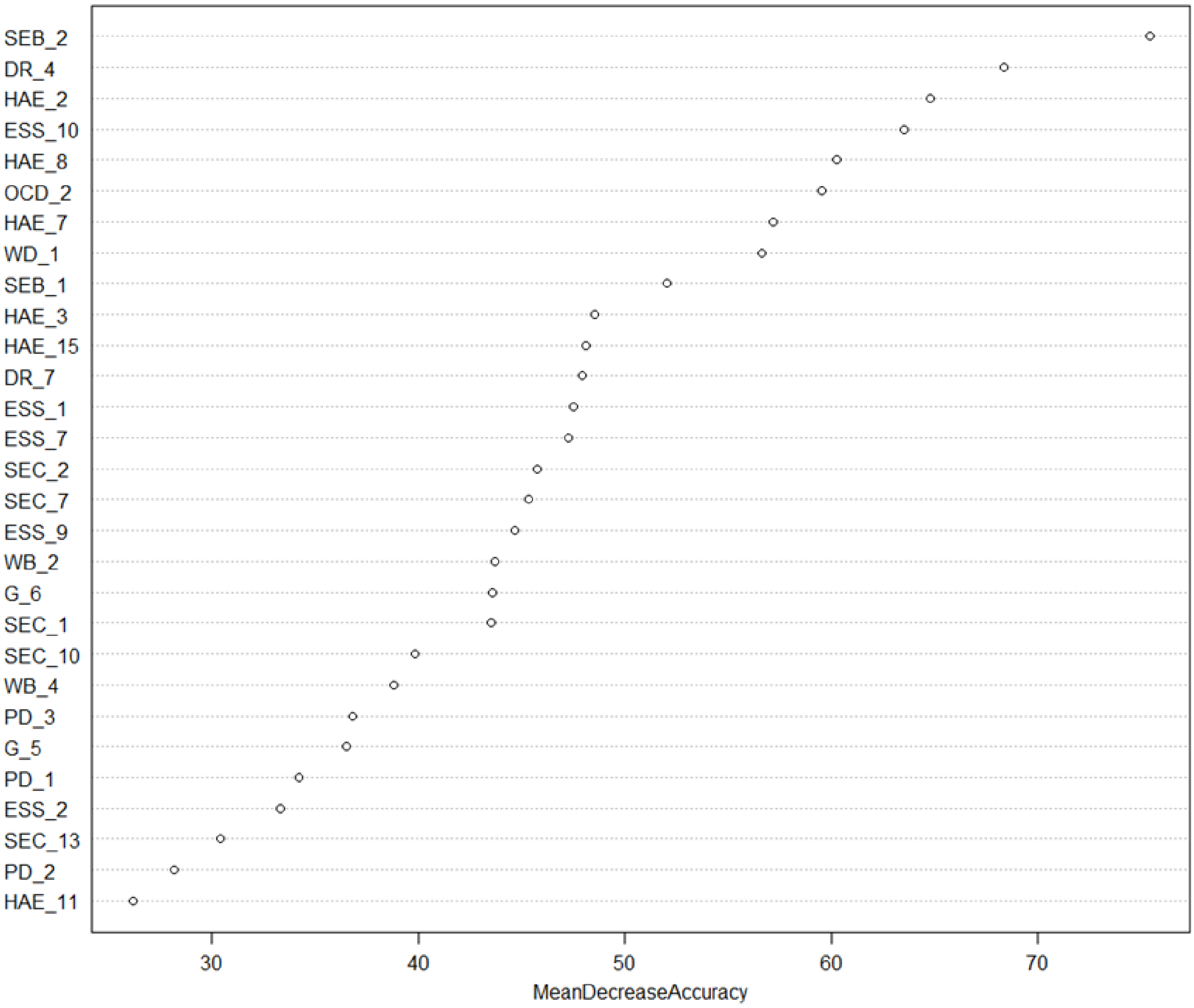


Fig. 2. Importance of the 29 selected indicators for social-ecological system mapping, provided by random forest analysis. The higher the value of the mean decrease accuracy index, the higher the importance of the indicator for the classification of municipalities into the SES clusters. **SEB_2**: mean annual temperature; **DR_4**: desertification rate; **HAE_2**: natural surface; **ESS_10**: landscape diversity; **HAE_8**: night sky quality; **OCD_2**: enhanced vegetation index coefficient of variation; **HAE_7**: greenhouse gas emissions in urban waste treatment; **WD_1**: mean annual precipitation; **SEB_1**: net solar radiation; **HAE_3**: cropland productivity; **HAE_15**: distance to capital city; **DR_7**: soil erosion rate; **ESS_1**: crop production; **ESS_7**: optimal suitability area for beekeeping; **SEC_2**: new employments in agriculture; **SEC_7**: rainfed crop production; **ESS_9**: carbon sequestration by terrestrial ecosystems; **WB_2**: unemployment rate; **G_6**: natural protected area; **SEC_1**: employments in agriculture; **SEC_10**: average farm area; **WB_4**: mean income; **PD_3**: population mean age; **G_5**: agricultural subsidies; **PD_1**: population density; **ESS_2**: livestock production; **SEC_13**: carbon dioxide emissions in goods transport; **PD_2**: population dispersion; **HAE_11**: total greenhouse gas emissions.

Map and characteristics of Andalusian SESs

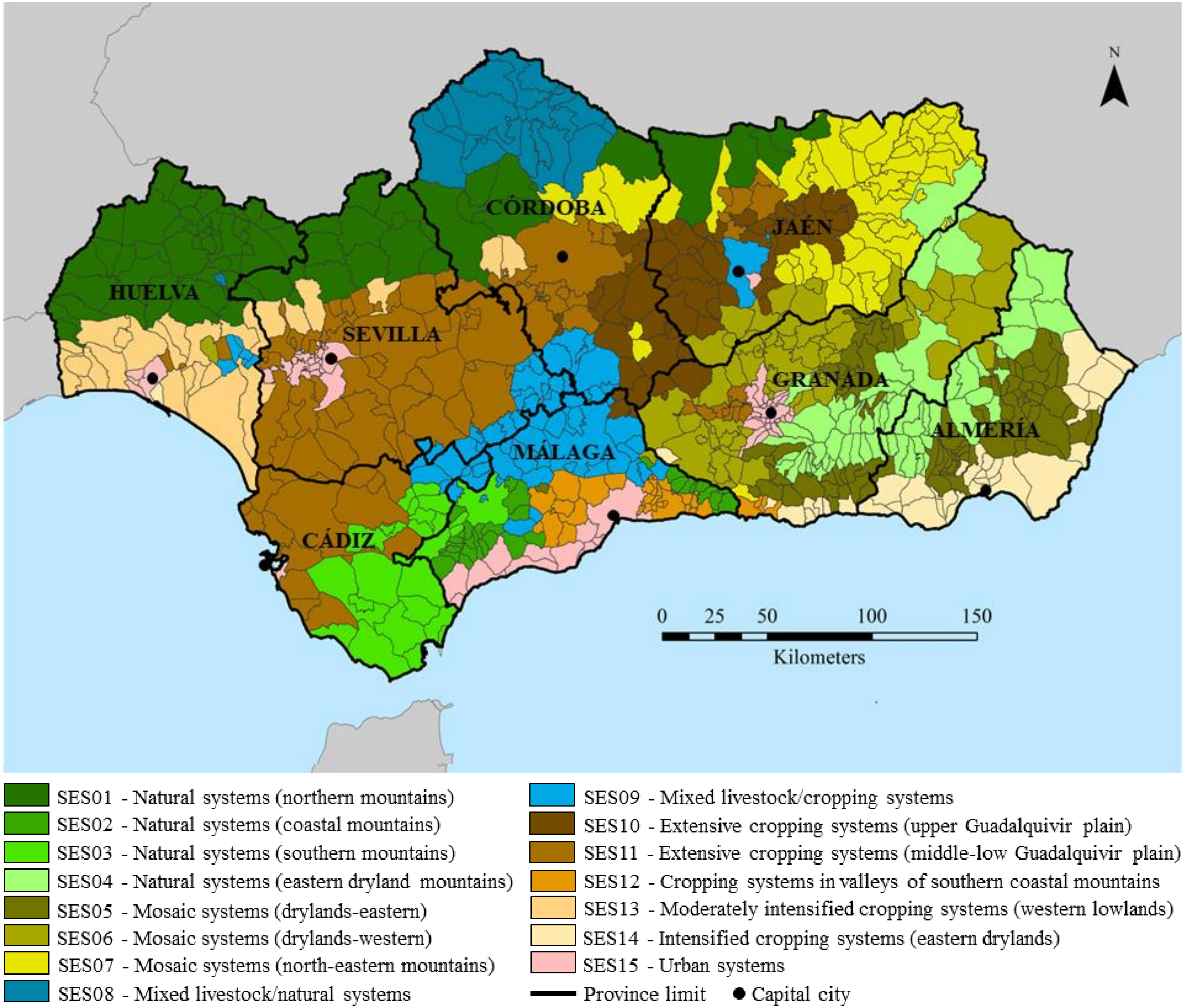
The 15 SESs identified through the 29 key indicators generally represented compact territorial units (Fig. 3; Appendix 2B, Fig. B3) that showed spatial coherence with other previous zonings of the Andalusian territory (e.g., landscapes units, *'comarcas'*, biogeographical sectors). We distinguished four main categories based on the land cover characteristics and activities developed in the system (Appendix 2B, Table B1). The "natural systems" category (SES01-SES04) encompassed those SESs dominated by natural areas (>70%) distributed across some of the main mountain ranges of the region. These SESs hosted the largest proportion of natural protected area, the highest night sky quality, and below-average (hereafter: low) territorial communication network connectivity (Table 1). In addition, natural systems showed the lowest crop production, but generally above-average (hereafter: high) supply of ecosystem services related to pollination and carbon sequestration. SES01, SES03, and SES04 had some of the greatest average farm areas. Interestingly, SES02 and SES03 presented one of the highest rates of urban waste production per inhabitant. Regarding the social system, the population mean age was high in SES01, SES02, and SES04. Concerning the ecological system characteristics, natural systems showed both the greatest (SES01, SES02, and SES03) and the lowest (SES04) mean annual precipitations of the study area. SES04 also had one of the lowest mean temperatures.

The "mosaic systems" category (SES05-SES07) represented mixed natural-agricultural landscapes. Mosaic SESs had a natural surface between 40 and 70%, intermediate/low crop production, a low proportion of natural protected area, and high night sky quality. These SESs also showed a high rate of employments and new employments in agriculture, and low incomes and agricultural subsidies. Regarding the ecological aspects, these systems generally showed low mean annual temperatures along with high desertification rates, specifically in eastern mosaics SES05 and SES06.

Within the "agricultural systems" category, we found SESs dominated by either livestock or cropping activities. On the one hand, livestock systems (SES08 and SES09) showed the highest livestock production in the study area. These SESs also showed a low proportion of natural protected area, and low territorial connectivity. Whereas SES08 had a high proportion of natural surface and marginal crop productions, SES09 showed one of the lowest rates of natural surface and on-average crop productions. In both cases, crop production was mostly rainfed. In terms of land tenure and agricultural subsidies, SES08 had a high average farm area and high subsidies, whereas SES09 showed the opposite. Similarly, SES08 had low landscape diversity and high carbon sequestration rate, whereas SES09 showed high and low rates, respectively. Outstandingly, SES08 showed the highest rate of GHG emission per inhabitant of the study area.

On the other hand, cropping systems (SES10-SES14) showed the highest crop productions. Across these SESs, we found a gradient of intensification positively correlated with the proportion of remaining natural surface. Thus, extensive cropping systems (SES10 and SES11) had the lowest cropland productivity and the lowest proportion of natural surface, whereas SES13 and SES14 were the most intensified and had a larger proportion of remaining natural surface. Generally, cropping systems had a low or very low proportion of natural protected area, high mean annual temperatures, and a reduced supply of regulating ecosystem services (i.e., the lowests carbon sequestration rates, and low optimal area for beekeeping). These SESs also presented low night sky quality, high territorial connectivity, and generally low GHG emissions. Some of the most intensified cropping systems (SES12 and SES14) were affected by desertification and even by high erosion rates (SES12). SES12 also showed the highest population dispersion. The social system of these SESs was characterized by an overall low population mean age.

Finally, the urban system (SES15) was the most densely populated, with very low population dispersion. This SES showed the lowest population mean age and the highest mean income, with the lowest proportion of employments and new employments in agriculture. Here, the proportion of natural surface, and the supply of provisioning (livestock production) and regulating (carbon sequestration, optimal area for beekeeping) ecosystem services were low. This SES showed the highest territorial connectivity and lowest night sky quality and, surprisingly, the lowest urban waste production and GHG emission rates per inhabitant.


N
CÓRDOBA
JAÉN
HUELVA
SEVILLA
GRANADA
ALMERÍA
MÁLAGA
CÁDIZ
0 25 50 100 150
Kilometers
SES01 - Natural systems (northern mountains)
SES02 - Natural systems (coastal mountains)
SES03 - Natural systems (southern mountains)
SES04 - Natural systems (eastern dryland mountains)
SES05 - Mosaic systems (drylands-eastern)
SES06 - Mosaic systems (drylands-western)
SES07 - Mosaic systems (north-eastern mountains)
SES08 - Mixed livestock/natural systems
SES09 - Mixed livestock/cropping systems
SES10 - Extensive cropping systems (upper Guadalquivir plain)
SES11 - Extensive cropping systems (middle-low Guadalquivir plain)
SES12 - Cropping systems in valleys of southern coastal mountains
SES13 - Moderately intensified cropping systems (western lowlands)
SES14 - Intensified cropping systems (eastern drylands)
SES15 - Urban systems
Province limit
Capital city

SES01 SES02 SES03 SES04 SES05
SES06 SES07 SES08 SES09 SES10
SES11 SES12 SES13 SES14 SES15

Fig. 3. Social-ecological system (SESs) map of Andalusia, Spain (page 102), and snapshots of representative landscapes of each SES (page 103): **SES01** - Sierra de Cardeña y Montoro Natural Park (Córdoba); **SES02** – Sierras de Tejeda, Almijara y Alhama Natural Park (Málaga); **SES03** – Los Alcornocales Natural Park (Cádiz); **SES04** – Sierra María-Los Vélez Natural Park (Almería); **SES05** – La Contraviesa (Granada); **SES06** – Montes Occidentales (Granada); **SES07** – Sierra de Segura (Jaén); **SES08** – Valle de los Pedroches (Córdoba); **SES09** – Montes de Málaga (Málaga); **SES10** – Olive orchards in La Loma (Jaén); **SES11** – Arable croplands in La Campiña de Sevilla (Sevilla); **SES12** – Fruit crops in Valle del Guadalhorce (Málaga); **SES13** – Arable croplands in La Campiña de Huelva (Huelva); **SES14** – Greenhouses in Campo de Dalías (Almería); **SES15** – Sevilla city (Sevilla). Please refer to Appendix 2B, Table B1 for a brief description of all SESs and their spatial coverage.

Table 1. Characterization of social-ecological systems archetypes based on the key indicators selected from the database (Appendix A; Table A.1). The larger the deviance from the study area average, the higher the impact of a given indicator on the respective SES. The + and - signs indicate whether an indicator is above or below the study area average; the absence of any sign indicates no substantial deviance from the study area average. We used the following thresholds: + from ≥ 0.5 up to 1 SD, ++ from ≥ 1 up to 2 SD, and +++ ≥ 2 SD. The same thresholds were applied to negative deviances. No substantial deviances were defined for SD between -0.5 and 0.5.

COMPONENT/*Dimension*/Indicator	Social-ecological systems														
	Natural				Mosaic			Agricultural							Urban
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
SOCIAL SYSTEM															
Human population dynamics															
Population density															+++
Population dispersion	-	++			+	-	-	--		-	-	+++		+	-
Population mean age	+	++	-	++	++			++			--		--	--	--
Well-being and development															
Unemployment rate	++		++	-			--	++		--	+	+	-	--	
Mean income		-	+		-	-	-			-	+			+	+++
Governance															
Agricultural subsidies		--			-	-	--	++	-	-	+	-	++	++	
Land protection	++		++	+++	-	-	+	-	-	-	-	-		-	
ECOLOGICAL SYSTEM															
Organic carbon dynamics															
NPP season. (CV annual EVI)	-	--			-		--	++		--	+++				
Water dynamics															
Mean annual precipitation	+	++	+++	-	--									--	
Surface energy balance															
Net solar radiation		-		++	-	+	--		+	--	+	--	++		+

Mean annual temperature		-		---	-	--	-				+	+	++	+	
Disturbance regime															
Desertification rate	-		--	+	++	+	-		-	-	-	++		++	
Soil erosion rate	-	++	+	-				--		+	-	+++	--		-
INTERACTIONS															
Ecosystem service supply															
Crop production	-	-	-	-	-			-			++	+		+++	
Livestock production		-		-			-	++	+++	-					-
Pollination	+++	+	++	-	-					-	-	-	++	-	-
Carbon sequestration	+++	+		+				+	-	--	-	--	++	--	-
Landscape diversity	--	++		+	+		-	--	+	-	--	++	+		
Human actions on the environment															
Natural surface	++	++	+	+	+			+	--	--	--	-			-
Cropland productivity						-							+	+++	
Urban waste production	-	+++	+				--		+		-	++	-	-	--
Night sky quality	++			+		+	+	+			-	-		-	---
Total GHG emissions	++							+++		-	-	-			--
Territorial connectivity	-	--	--	-			--	-	-	+	+	++	++		++
Social-ecological (de)coupling															
Employments in agriculture		+	--		+	++	++			++	--		--	-	--
New employments in agriculture		-	--	-		++	++	-	+	++			+		--
Rainfed crop production	+		+	--	--			++	++	+		-	-	--	-
Land tenure (farm area)	++	-	+++	+			-	++	-	-		-		-	-
Transport of goods	-	++	--		+		+				-		-	+++	--

Comparison of empirical and expert knowledge on the relevance of variables to characterize and map SESs

First, we identified two groups of variables that were both prioritized by experts and empirically selected to be used for SES mapping (groups B and C; Fig. 4). Group C (30.6% of the variables) encompassed a set of variables that 1) have been widely used across contexts and scales to map SESs, 2) were considered relevant by expert knowledge, and 3) were generally useful in our study area. These variables represented aspects of the social system (e.g., population density, population distribution), the ecological system (e.g., seasonality, temperature, soil erosion) and the interactions between them (e.g., crop and livestock production, land use intensity, territorial connectivity). Within group B (18.4% of the variables) we identified a set of variables also considered relevant by expert knowledge, but only used for SES mapping in local and regional contexts. In our study area, some of these variables were relevant to map SESs (e.g., local natural capital dependence, land protection), whereas others were discarded throughout the screening process, either for being highly correlated (e.g., educational level, evapotranspiration, water deficit or excess), or for not being useful to discriminate among SESs (e.g., water use).

Second, groups E and F encompassed variables (18.4%) that were considered non-priority by expert knowledge but used for SES mapping. In group F, the economic level variable was widely used across scales and also useful to identify SESs in our study area through the indicator mean income. Group E included variables only used in local and regional contexts, and some of them were also useful in our study area (e.g., employment, land tenure, population ageing).

Third, we identified two groups of variables (24.5%) that were assessed by experts but not used in other SES mapping studies (groups A and D). On the one hand, group A included those variables considered of high relevance by experts (e.g., drought occurrence, energy use, social equity). In our case study, these variables were discarded given that the specific indicators used were not useful to discern among SESs. On the other hand, group D gathered those variables considered non-priority by experts. However, some indicators that we used to explain them were relevant in our study area (e.g., related to anthropogenic GHG emissions and traditional/organic agriculture).

Fourth, two additional groups (H and I) included variables (4.1%) used in SES mapping, but not assessed through expert knowledge (e.g., urban waste production, habitat maintenance/biodiversity). Finally, group G illustrated examples of variables (4.1%) that were neither assessed by expert knowledge nor used in other SES mapping studies (e.g., desertification, rainfall torrentiallity).

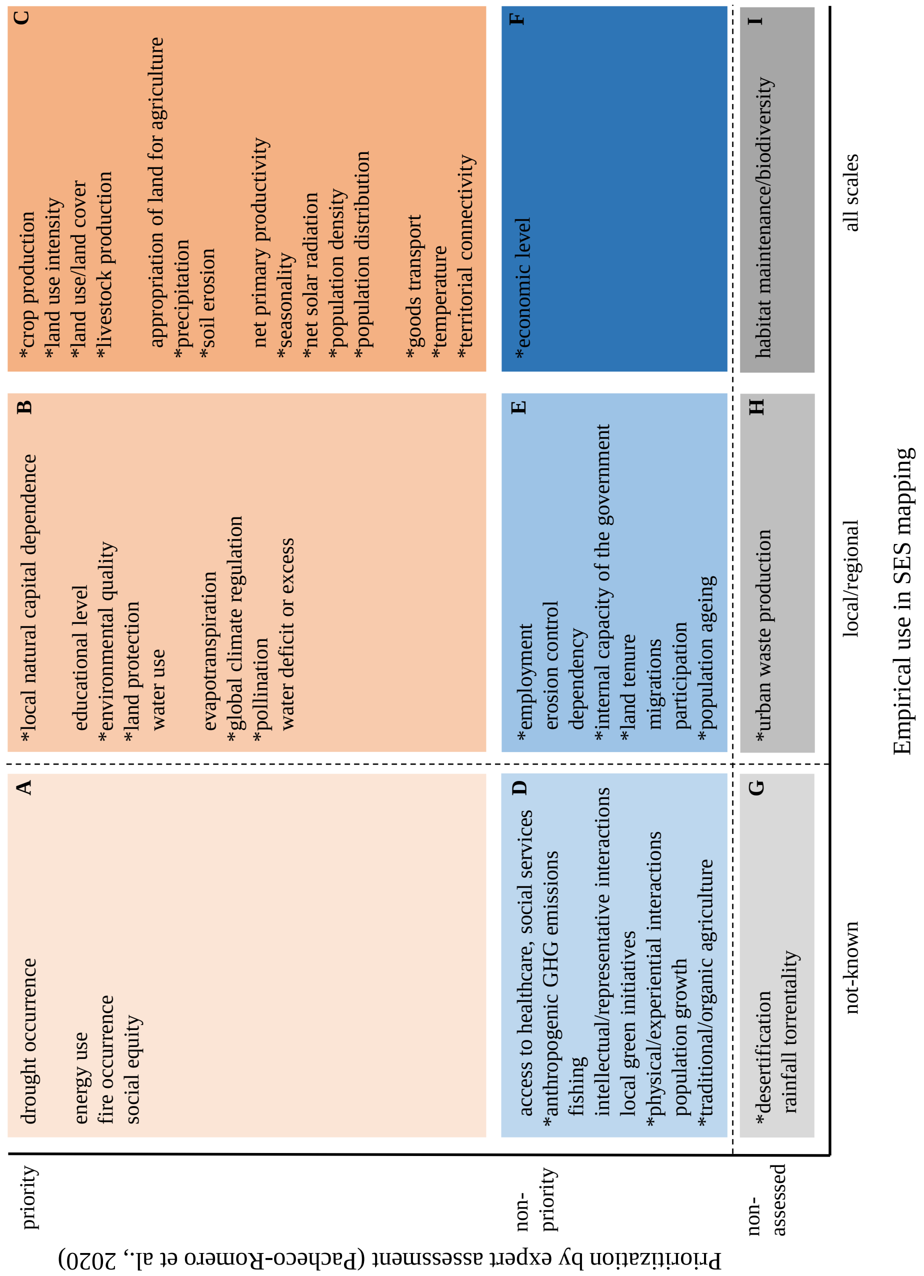


Fig. 4. Comparison of empirical and expert knowledge on the relevance of variables to characterize and map SESs, based on: 1) the use of the variables in other SES mapping studies (in local/regional scales or across scales); 2) their relevance according to expert knowledge (following the reference list of Pacheco-Romero et al., 2020); and 3) their relevance for our specific case-study (*). The subgrouping of the variables within groups A, B and C reflect the different priority levels set by the expert assessment, from highest (top) to lowest priority (bottom). Note that here we assessed the 49 variables characterized by the 86 indicators analyzed in our study (please refer to Appendix 2A, Table A1).

DISCUSSION

The spatial mapping of social-ecological systems constitutes a fundamental tool to operationalize the social-ecological approach in empirical and applied research. However, after a decade of research progress in this field, conceptual and methodological pluralism is hampering the synthesis and comparison of results (de Vos et al., 2019). Thus, the current challenge is to develop approaches that foster the potential of SES mapping to produce more generalizable knowledge (Dressel et al., 2018; Rocha et al., 2020). We propose a data-driven methodological routine based on multivariate statistical analysis to identify the key (relevant and independent) indicators for mapping and characterizing the diversity of SESs. First, applying this routine to an integrative database of 86 indicators allowed us to identify 29 key indicators and map 15 SES archetypes for Andalusia region (Spain). These archetypes contributed to disentangling the complexity of human-nature interactions across landscapes, and uncovered a nested pattern of land sparing and land sharing strategies. Second, contextualizing the empirical relevance of the indicators used in this study within general expert and empirical knowledge on key variables for SES characterization revealed points of synergy but also of disagreement. These findings allowed us to understand how our approach may contribute to produce more general and comparable knowledge on key variables for characterizing and mapping SESs.

Social-ecological system archetypes disentangle complex human-nature interactions across landscapes

The identified key indicators allowed us to explain the diversity of SES archetypes in Andalusia, and to structure the social-ecological complexity of the territory. These archetypes mostly represented typical cultural landscapes of the Mediterranean region, and reflected specific combinations of social and ecological characteristics, patterns and outcomes of human-nature interactions, and social-ecological trade-offs across them. In addition, the use of a conceptual framework and a reference list of variables (Pacheco-Romero et al., 2020) to structure our indicator's database facilitated to connect locally relevant indicators with globally recognisable variables, and thus to better contextualize and upscale the generated knowledge in our case-study (Cox et al., 2020; Guerra et al., 2019).

The main social-ecological trade-offs within and among agricultural, mosaic and natural SESs uncovered a nested pattern of land sparing and land sharing strategies across the study area (Fischer et al., 2008). Overall, the region was dominated by a land sparing pattern between the agricultural and natural SESs. We observed a clear spatial segregation between agricultural SESs occupying the most suitable topographical conditions, and natural SESs mainly located in mountainous areas. This sparing pattern was repeated throughout all the sub-regions (provinces) of the study area. However, some provinces showed a sharp spatial transition between agricultural and natural SES (e.g., Cádiz, Huelva, Sevilla, Córdoba), whereas in others (e.g., Almería, Granada), such transition was more gradual from agricultural to mosaic, and natural SESs.

On the one hand, agricultural SESs (SES08 - SES14) maximized the supply of provisioning ecosystem services (i.e. crops and livestock) at the expense of regulating ecosystem services (i.e. pollination and carbon sequestration), and showed distinct land transformations and land use intensities across the study area. The dominance of these SESs evidenced the crucial role of agriculture in Andalusia to sustain regional food production (Ibarrola-Rivas et al., 2020; Malek & Verburg, 2017). Cropping systems ranged from extensive olive orchards monocultures (SES10) and diverse arable and woody crops along the Guadalquivir and Genil valley (SES11), to subtropical fruit crops in coastal mountains of Málaga and Granada (SES12) and intensified cropping systems in coastal plains of Huelva and Almería (SES13 and SES14). As in other agricultural systems across the Mediterranean basin, the areas through which these SESs are distributed had higher mean annual temperatures, and higher territorial connectivity (Malek & Verburg, 2017). In our study area, precipitation showed a decreasing gradient from west to east. Thus, the aridity of eastern territories and the highly intensified agricultural SESs (e.g., SES14) evidence the decoupling of the productivity of these systems from the natural primary productivity of the region. Regarding livestock systems (SES08 and SES09), they occupied less favourable areas for agriculture and constituted mixed systems that include natural and cropland areas. For instance, SES08 mostly occupied open woodlands (dehesas) in the north of Córdoba province, a singular agroecosystem with significant ecological value where livestock (mainly iberian pigs, but also sheeps and cows) is extensively managed (Joffre et al., 1999; Ríos-Núñez et al., 2013). On the other hand, natural SESs showed a high supply of regulating ecosystem services at the expense of provisioning services. These systems encompassed those areas less intensely transformed by human activity, which hosted the greatest rates of surface covered by natural or semi-natural ecosystems.

Below this general sparing pattern, agricultural and natural SESs represented in themselves distinct configurations of land sparing and land sharing strategies, respectively. For instance, within agricultural SESs (cropping systems), we found that the extent of the remaining natural surface was proportional to the level of intensification. Thus, the most intensified cropping systems of the region, located in eastern drylands (SES14), hosted the largest proportion of natural surface (c.a. 60%) of all cropping systems. Here, high-yield industrialized croplands targeted at maximum economic efficiency have been strongly segregated from natural habitats, which are protected from agricultural conversion (Castro et al., 2014, 2015; Piquer-Rodríguez et al., 2012). This strategy promotes separation of humans from nature (Fischer et al., 2008) and involves telecouplings due to distant food trade (Ibarrola-Rivas et al., 2020). Achieving a sustainable intensification is one of the major challenges of these typical "frontier landscapes" undergoing rapid land conversion (Castro et al., 2019; Fischer et al., 2008; Martínez-Valderrama et al., 2020b). Conversely, the least intensified cropping systems located along the Guadalquivir valley (SES10 and SES11) hold the smallest natural surface of all SESs (c.a. 10-12%, respectively). These landscapes, where the topography and land tenure structure favored the homogenization and expansion of croplands, have a long agricultural history through which natural ecosystems have been reduced to small islands or narrow strips between fields and along riverbanks. Here, management strategies should be targeted principally to protect patches of native vegetation, create connections among them, and increase landscape heterogeneity, for instance, through agricultural diversification (Fischer et al., 2008).

In contrast, natural SESs (SES01 - SES04) hosted more wildlife-friendly practices, approaching a land sharing strategy. Rather than pristine ecosystems, these SESs constitute cultural landscapes dominated by forests, shrublands and grasslands linked to traditional and extensive silvopastoral uses (e.g., wood harvesting for heating, cork harvesting, extensive livestock breeding, trashumance), local ecological knowledge, and high biodiversity rates (Hartel et al., 2018; Malek & Verburg, 2017; Oteros-Rozas et al., 2013; Plieninger et al., 2015). In these landscapes, the biophysical properties of the territory (e.g., complex topography, poor soils), and the socioeconomic and historical context (e.g., historical land ownership) have hampered the implementation of industrial agriculture (Fischer et al., 2008). Additionally, the declaration of protected areas over these SESs has favoured landscape preservation under a land sharing strategy. However, land use abandonment is often one of the main threats of these SESs, where biodiversity conservation and landscape heterogeneity depends on the maintenance of agricultural traditional activities (Halada et al., 2011; Plieninger et al., 2015).

At an intermediate point in the continuum between land sparing and land sharing strategies were mosaic systems (SES05 - SES07). These SESs hosted a similar proportion between agricultural and natural areas, and showed a more balanced supply of provisioning and regulating services. They were mainly distributed in eastern Andalusia, and had generally lower mean annual temperatures and lower human pressure. Here, the complex topography has favoured a landscape with an intermediate spatial grain, which increases ecological interactions between natural vegetation and croplands (Fischer et al., 2008). In these systems, the dependence on local natural capital was high, with one of the greatest proportions of employment in agriculture. Overall, mosaic systems represent multifunctional cultural landscapes throughout the Mediterranean basin, which integrate high biodiversity and cultural heritage values, and have an important role for regional food production (Malek & Verburg, 2017).

Finally, urban SES (SES15) appeared only in specific locations. The spatial resolution (municipality level) of the data could have masked crucial factors for the identification of urban SES such as population density. Thus, we only identified as urban SESs those big urban agglomerations located in relatively small municipalities, even though the Andalusian population mostly inhabits compact urban areas across the region. Therefore, the majority of villages, towns, as well as those capital cities located in large municipalities (e.g., Almería, Córdoba, Jaén) were not classified as urban SES, but embedded in wider agricultural SESs.

Integrating empirical and expert knowledge: insights towards essential SES variables

The assessment of the 49 variables characterized by the 86 indicators used in our analysis (Appendix 2A, Table A1) allowed us to understand how our approach may contribute to the general knowledge on key variables for SESs. We found synergies between expert and empirical knowledge on the relevance of variables from group C for SES characterization and mapping (Fig. 4). Additionally, the wide use of these variables across scales evidenced that such relevance is scarcely dependent on the context (e.g., Ellis and Ramankutty, 2008; Martín-López et al., 2017; Rocha et al., 2020; Václavík et al., 2013; Vallejos et al., 2020). Thus, the universality of these variables to map SESs and the agreement on their importance could make them suitable to be considered as potential candidates to essential SES variables (Guerra et al., 2019; Reyers et al., 2017). In fact, these variables could meet some criteria to be considered essential such as the representativeness for the system level, the adaptability to the context or data availability, and the feasibility to be derived and scaled to meet local, regional or global needs (Reyers et al., 2017).

In the case of group B variables we observed a similar agreement, although the empirical evidence suggested that the use of these variables for SES mapping is more conditioned by the context (e.g., Castellarini et al., 2014; Hamann et al., 2015; Levers et al., 2018; Queiroz et al., 2015). In this sense, knowing variables whose relevance depends on the context or scale of analysis can be also fundamental to represent the diversity and particularities of SESs of a specific region (Dressel et al., 2018; Rocha et al., 2020; Vallejos et al., 2020). In a hypothetical list of essential SES variables, such context-dependent variables could be included in a lower level than more universal variables (e.g., group C variables). Thus, hierarchical structures and frameworks to organize reference lists of variables can facilitate a more flexible use, which is crucial to promote comparisons and knowledge generalization among case studies (Frey, 2017; McGinnis and Ostrom, 2014; Ostrom, 2009).

Conversely, for group E and F variables, the lack of agreement between expert and empirical knowledge (i.e., variables considered non-priority by experts but widely used in SES mapping) yielded a more uncertain conclusion. The high data availability could have promoted a wide use of the variable economic level (group F) through diverse indicators such as gross domestic product (Václavík et al., 2013), household income (Hamann et al., 2015), and income per capita (Martín-López et al., 2017). However, its perception as non-priority might reflect the attempts from sustainability research to avoid assessing social well-being through economic indicators (Costanza et al., 2016; Fioramonti et al., 2019; Helne & Hirvilammi, 2015). Similarly, the high data availability could explain the wide use of group E variables in SES mapping (e.g., Dittrich et al., 2017; Dressel et al., 2018; Martín-López et al., 2017), although their classification as non-priority variables might be influenced by the higher context-dependence of variables' relevance. In both cases, further expert assessments could help to unravel this contradiction by considering specific contexts when evaluating variable relevance.

In the case of the groups A and D, the lack of data availability could be limiting the use of suitable indicators to incorporate these variables in SESs mapping (Rocha et al., 2020), especially in group A variables, which were prioritized by experts. However, both the unknown use and non-prioritization of variables from group D might indicate their lower relevance. Since we found some specific indicators that were useful to map SESs in our study area (e.g., related to variables such as anthropogenic GHG emissions and traditional/organic agriculture), we encourage new empirical assessments that help to unveil additional relevant variables from this group.

Finally, our analysis revealed variables that were crucial to map SESs in our study area, but neither assessed by experts nor used in previous SES mappings, such as desertification (group G). This variable may not be appropriate in some environmental conditions but should be useful in other arid regions, if data were available (Martínez-Valderrama et al., 2020a). In this sense, some variables that were not included in the expert assessment have been useful in SES mapping. For instance, the variable urban waste production (group H), was used in our study area and in other local contexts of Andalusia (Martín-López et al., 2017). Additionally, indicators related to biodiversity and habitat maintenance variables (group I) were widely used for SES mapping across scales, such as species richness (Hanspach et al., 2016, Spake et al., 2017; Václavík et al., 2013), or distribution of ecoregions (Castellarini et al., 2014; Levers et al., 2018). Overall, these examples showed the importance of exploring the relevance of new variables in future expert and empirical assessments.

Overall, we evidence the importance of combining insights from expert and empirical assessments to identify critical variables for SES mapping and characterization. Specifically, the application of our data-driven approach could help to accumulate empirical knowledge on the most relevant variables across contexts and scales, and contribute to expert-based assessments for the development of reference lists of variables for SESs (e.g., Cox, 2020; Frey, 2017; Guerra et al., 2019; Ostrom, 2009; Pacheco-Romero et al., 2020; Reyers et al., 2017). Although we identified variables of universal relevance, the role of variables whose relevance is more context-dependent should not be underestimated, because they could be equally necessary to characterize SESs in a given region. In fact, one of the current challenges facing SES research is to identify which characteristics and patterns are more generalizable, and which are context-specific (Balvanera et al., 2017; Magliocca et al., 2018; Rocha et al., 2019).

As in other fields of the Earth system (climate, biodiversity, oceans), lists and repositories of reference variables will become a cornerstone for developing more consistent research and monitoring of SESs (Cox et al., 2020; Holzer et al., 2018; Mirtl et al., 2018). The studies that have so far proposed reference lists of variables for the study of SESs agree on the need to use a shared language to harmonize the way we analyze these complex systems (e.g., Cox et al., 2020; Frey, 2018; Ostrom, 2009; Pacheco-Romero et al., 2020). As scientific evidence suggests, one of the main challenges for developing lists of essential SES variables could be to integrate both universal and context-dependent attributes, organized in hierarchical structures (Cox et al., 2020; Ostrom, 2009). It will contribute to connect locally relevant indicators with globally essential variables (Guerra et al., 2019), which might improve our capacity to obtain more comparable results, produce generalized knowledge, and foster theory development on SESs (Magglioca et al., 2018; Meyfroidt et al., 2018).

Limitations and recommendations for future research

The empirically selected indicators of this study must be considered as a context-specific result, since they refer to a specific study area, and therefore treated cautiously. Generally, variables incorporated in SES mapping are measured through diverse indicators. Thus, the relevance of the variables reported in our case study can be dependent on the specific indicators used to explain them, and on the quality of the data. Other studies could have selected distinct indicators for the same variables, or explained other variables from the same indicators, based on the context or data availability. For this reason, further empirical research is needed to accumulate knowledge on the relevance of indicators to map SES across regions.

Overall, researchers should pay special attention to data preprocessing (e.g., standardization of indicators), since it is a fundamental step within the whole mapping process that can determine the performance of indicators to detect and characterize SESs. For instance, in our case study, indicators related to greenhouse gas emissions, which were standardized per inhabitant, were not generally useful to detect SESs (e.g., CO2 emissions in energy consumption by socioeconomic sectors). In addition, some of the used indicators (e.g., total GHG emissions, and GHG emissions in urban waste treatment) showed surprising results after SES characterization. For example, some agricultural or even natural SES showed higher emission rates than urban SES. We suspect that standardizing these indicators per inhabitant, rather than per area, could have masked the impact of the indicator in the most densely populated SES, or magnify it in the least populated ones. Perhaps, standardizing GHG-related indicators per area might better reflect the different contributions of the SESs to GHG emissions.

Finally, the resolution at which SESs are mapped is another aspect that should be carefully considered. Although the municipality level is a representative scale for social processes and decision making, and usually the most detailed scale at which official statistics are compiled (Martín-López et al., 2017; Raudsepp-Hearne et al., 2010), the use of finer resolutions could help to uncover SESs that are hidden in large municipalities (e.g., urban SES embedded in wider agricultural SES).

CONCLUSIONS

Social-ecological system archetype mapping is a powerful approach to produce empirical and systematic knowledge on the spatial distribution and characteristics of SESs across regions. However, the conceptual and methodological pluralism that characterizes SES mapping approaches is hampering the production of comparable knowledge that can be scaled or transferred to other contexts. The selection of indicators is a fundamental aspect for SES mapping, as it greatly conditions the identification of their spatial limits, as well as the interpretation of the identified systems. Despite the progress made towards developing more harmonized databases, based on conceptual frameworks and reference lists of variables, approaches to evaluate the most relevant indicators for SES mapping in a given region have not yet been developed. Here we propose a repeatable data-driven methodological routine to assist the selection of the most relevant indicators to map the diversity of SES in a region. The application of this approach to Andalusia (Spain), using a wide database of potentially relevant indicators, showed substantial differences in their usefulness for discriminating among SESs in this region. Therefore, these results, and the method itself, can foster the potential of SES mapping to contribute to place-based social-ecological research aims, by producing: 1) more comparable SES mappings based on a more objective selection of the key indicators leading their distribution, and 2) generalizable knowledge on the most relevant variables to characterize SESs across contexts and scales that guides the identification of essential SES variables. Our study also opens a reflection on the importance of combining expert and empirical insights in the identification of essential variables, and on one of the probable challenges in the development of these lists for SES: the integration of both universal and context-specific relevant variables.

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

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ABSTRACT

Archetype analysis is a key tool in landscape and sustainability research to structure 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 among 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 typologies 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 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. It 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.

Keywords: Coupled human and natural systems; human-nature connectedness; landscape change; nested archetypes; spatial clustering; sustainability.

INTRODUCTION

Understanding the interactions between people and nature is at the heart of addressing all major sustainability problems we face in the Anthropocene. 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 structure 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 (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 & 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., 2019), 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, or Levers et al. (2018) mapped archetypical changes of European land systems. All these studies contribute empirical evidence on SES configuration and dynamics, but the diverse SES conceptualizations, research questions, methods used, and social-ecological contexts make it difficult to compare from case to case (Balvanera et al., 2017b). This 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-nature relations (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, describing the level of dependence of societies on local natural capital. 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 (e.g., through hierarchical typologies) (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 et al., 2017a; Fischer et al., 2017; Magliocca et al., 2018; Václavík et al., 2016).

Despite these advantages, approaches that link inductive and deductive perspectives are very scarce. In fact, we know of only one study, by Hamann et al. (2015), integrating 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. 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 km2) 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-nature relationships.

In this context, we asked the following research questions:

1. What are the typical SESs and the social-ecological changes that have shape them, as identified by an inductive, spatio-temporal archetype approach?

2. How do these inductive SESs map onto deductive typologies of human-nature connectedness?

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) (Appendix 3A, Fig. A1). 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 typologies (based on Cumming et al., 2014, and Dorninger et al., 2017) that classify SESs according to their human-nature connectedness (Fig. 1A).

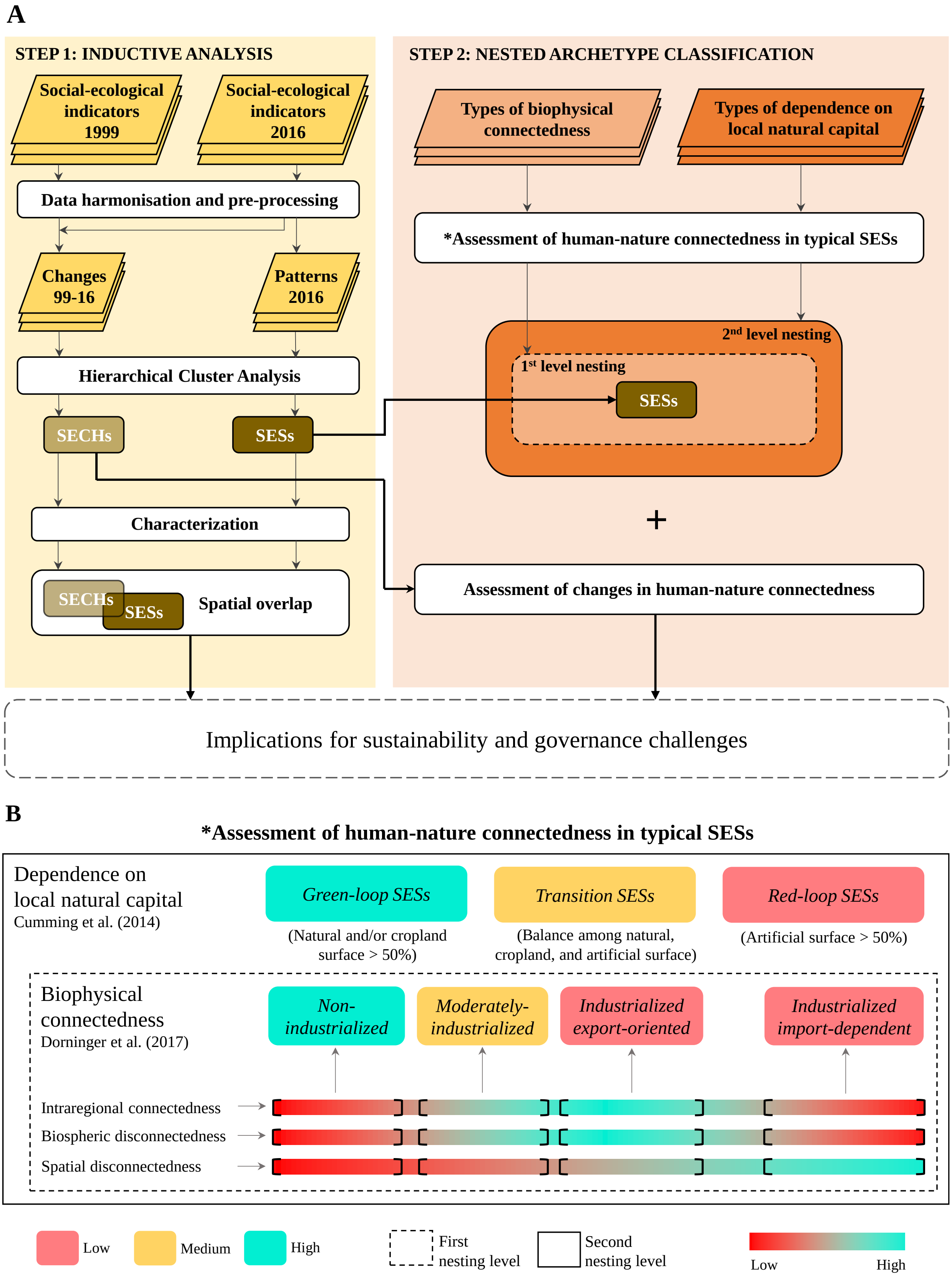


Fig. 1. (A) Main steps for linking inductive and deductive analyses to derive a nested archetype classification. Left (yellow box): data-driven analysis for detecting and mapping typical social-ecological systems (SESs) and changes (SECHs) therein. Right (orange box): deductive assessment of typical SESs and SECHs to derive a nested archetype classification. (B) Detailed view of the

nested archetype classification. The first nested level categorises SESs according to their biophysical connectedness (Dorninger et al., 2017). The second nested level groups archetypes further according to their dependence on local natural capital (Cumming et al., 2014).

Database development

We developed a dataset of 26 indicators, pertaining to the social system (e.g., population density, population mean age, public expenditure), ecological system (e.g., mean annual enhanced vegetation index, mean annual precipitation, mean drought standardized index) and interactions between them (e.g., crop production, livestock production, greenhouse gas emissions), using open access regional databases (Appendix 3A, Table A1). We harmonized all indicators at the municipality level (n=778 municipalities) for the years 1999 (t0) and 2016 (t1). For indicators that were unavailable for t0 or t1, 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. 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 3A.

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. 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 3A, Table A2). 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).

Deductive assessment of archetypes

After identifying typical SESs (for 2016) and SECHs (between 1999-2016), we assessed and interpreted them in terms of human-nature connectedness (Fig. 1B). Specifically, we developed a nested archetype classification that at the first level associated each typical SES to a set of deductive typologies describing the biophysical connectedness between humans and nature (Dorninger et al., 2017). To assess biophysical connectedness, we evaluated three dimensions using proxies from our database (Appendix 3A, Table A3). The first dimension 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. Once proxies for each of these dimensions were analysed in each SESs, we classified them into four deductive typologies (i.e., non-industrialized, moderately industrialized, industrialized export-oriented, and industrialized import-dependent), from high to low biophysical connectedness. 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), which distinguishes three deductive typologies (i.e., green-loop, transition, and red-loop) based on their dependence on local natural capital. We used the proportion of natural, cropland, and artificial surfaces as proxies of such dependence. Thus, the dominance of natural and/or cropland surfaces (>50%) was associated with a higher dependence on local natural capital and therefore to green-loop SESs. Conversely, the dominance of artificial surface (>50%) was associated to a lower dependence on local natural capital, which characterizes red-loop SESs. A balance among natural, cropland, and artificial surfaces (c.a. one third of the total surface for each) was associated to intermediate dependence on local natural capital, and therefore to transition SESs.

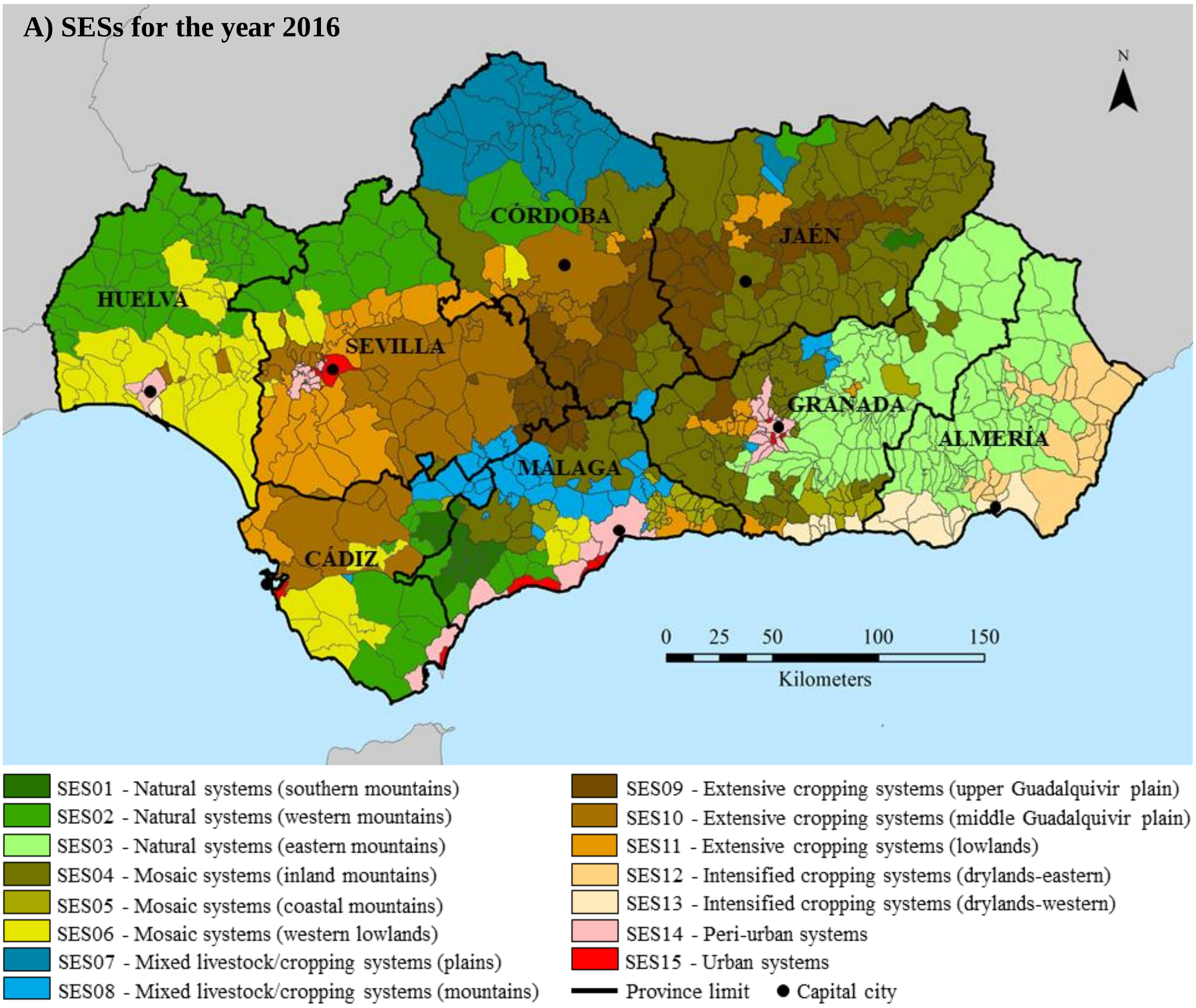
RESULTS

Detecting and mapping typical SESs and their changes

We identified and mapped 15 typical social-ecological systems (Fig. 2A; Appendix 3B, Table B1). 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 3B, Table B3). 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. 2B; Appendix 3B, Table B2). SECHs lead by agricultural expansion and/or intensification (from SECH01 to SECH05) were widespread across our study region (46% coverage). These changes included strong 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 3B, Fig. B1). 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 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 3B, Fig. B2). We found that stability (SECH12) had the largest spatial extent (Appendix 3B, Table B4), 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 3B, Fig. B2.A), 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 3B, Fig. B2.B), 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).


A) SESs for the year 2016
N
HUELVA
SEVILLA
CÓRDOBA
JAÉN
GRANADA
ALMERÍA
MÁLAGA
CÁDIZ
0 25 50 100 150
Kilometers
SES01 - Natural systems (southern mountains)
SES02 - Natural systems (western mountains)
SES03 - Natural systems (eastern mountains)
SES04 - Mosaic systems (inland mountains)
SES05 - Mosaic systems (coastal mountains)
SES06 - Mosaic systems (western lowlands)
SES07 - Mixed livestock/cropping systems (plains)
SES08 - Mixed livestock/cropping systems (mountains)
SES09 - Extensive cropping systems (upper Guadalquivir plain)
SES10 - Extensive cropping systems (middle Guadalquivir plain)
SES11 - Extensive cropping systems (lowlands)
SES12 - Intensified cropping systems (drylands-eastern)
SES13 - Intensified cropping systems (drylands-western)
SES14 - Peri-urban systems
SES15 - Urban systems
Province limit
Capital city

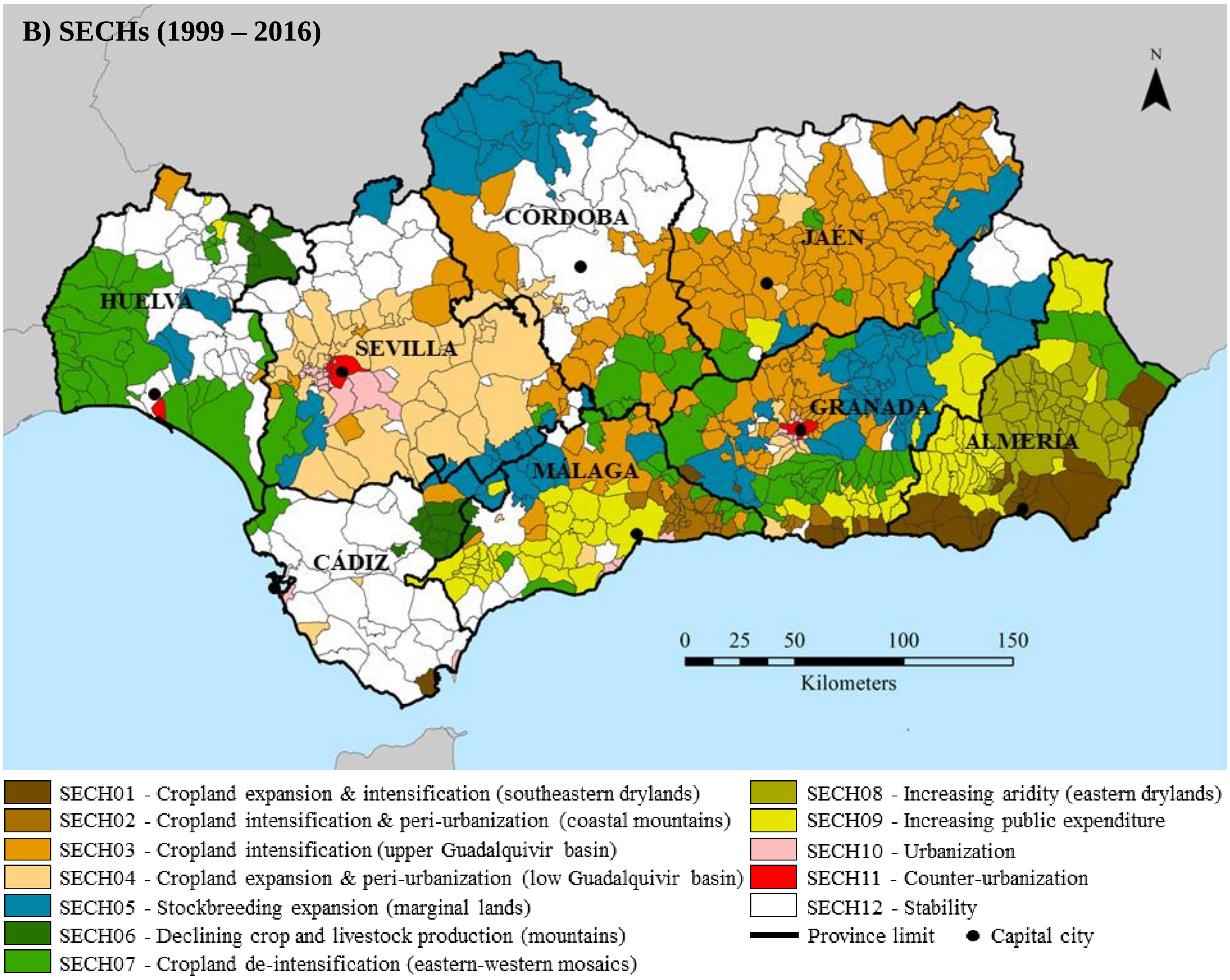

B) SECHs (1999 – 2016)

Fig. 2. 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 3B, Tables B1 and B2 for a description of all SESs and SECHs.

Deductive assessment of archetypes

Assessing the inductively identified typical SESs based on our two-level, nested scheme of deductive typologies 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. 3A). Thus, these SESs reflected the highest biophysical connectedness and were classified as non-industrialized (Fig. 1B). 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. 3B), 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.

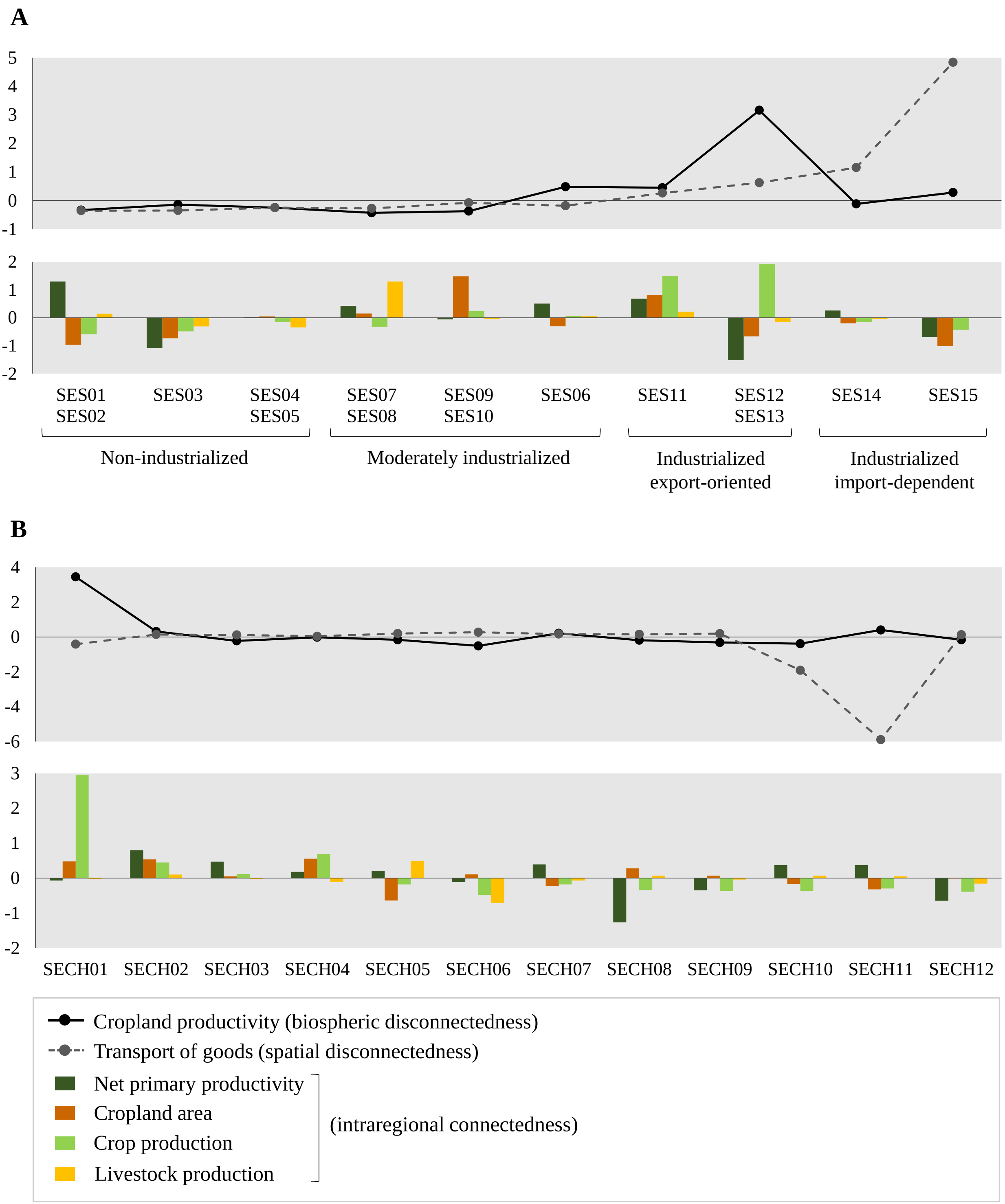


Fig. 3. Assessment of the dimensions of biophysical connectedness for the typical SESs of Andalusia (2016) (A), and variations in dimensions associated to typical SECHs (1999-2016) (B). Black solid line indicates cropland productivity levels as a proxy for biospheric disconnectedness (high productivity = low connectedness). Grey 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.

Categorizing typical SESs further in our second-level classification revealed that all SESs dominated by natural and/or cropland surfaces (SES01-SES13) were classified as green-loop SESs (Fig. 4), and therefore as highly dependent on local natural capital (Appendix 3B, Fig. B3). On the other side, SES15, dominated by artificial surfaces, exemplified a red-loop SES, with low dependence on local natural capital. Regarding SES14 (peri-urban systems), despite also representing an industrialized import-dependent system, it was classified as a transition SES for having a balance among natural, cropland, and artificial surfaces, which suggested an intermediate dependence on local natural capital. 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 dependence on local natural capital and high biophysical connectedness). Such connectedness declined throughout the rest of agricultural SESs (i.e., high dependence on local natural capital, but lower biophysical connectedness), to a minimum in peri-urban and urban systems (SES15) (i.e., low dependence on local natural capital and low biophysical connectedness).

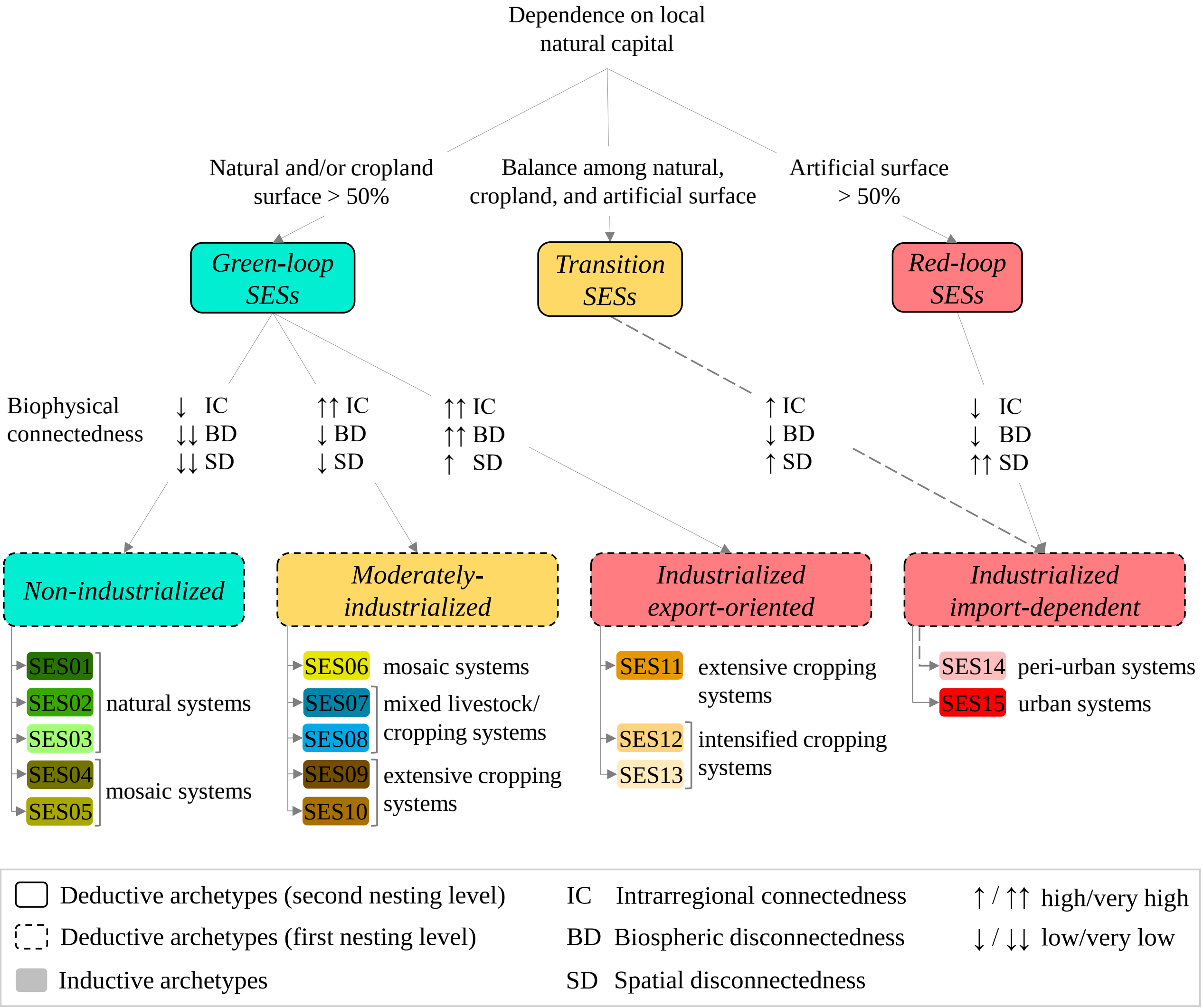


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Fig. 4. Summary of the nested classification of inductive typical SESs within the deductive typologies proposed by Dorninger et al. (2017) and Cumming et al. (2014). Blue, yellow, and red boxes represent high, intermediate, and low levels of biophysical connectedness and dependence on local natural capital of the deductive typologies. The criteria used to differentiate among deductive typologies are shown along the arrows. Background colour for inductive SESs follows the colour code of Fig. 2A.

DISCUSSION

Understanding archetypical patterns and changes in social-ecological systems (SESs) is important for structuring the complexity of social-ecological processes influencing landscape change - and thus ultimately for furthering theory in landscape and sustainability science. 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 socio-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.

Describing typical social-ecological changes improve SES characterisation

The incorporation of a spatio-temporal perspective helped to characterize SESs in our study region. First, the 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. 2; Appendix 3B, Fig. B2). This supports views that intensification has been the central land-use change in Andalusia recently (Muñoz-Rojas et al., 2011), particularly the expansion of 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 structure 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).

Gradients of human-nature connectedness

Analysing our typical SESs through the deductive typologies proposed by Cumming et al. (2014) and Dorninger et al. (2017) provided substantial additional interpretive power. First, we found that the levels of intraregional connectedness, biospheric disconnectedness, and spatial disconnectedness across our SESs represented the range of industrialization levels defined by Dorninger et al. (2017), 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 dependence on local natural capital associated with the typologies defined by Cumming et al. (2014). 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. Likewise, changes in the dependence on local natural capital were mainly associated with (peri)urbanization. Thus, green-loop and non-industrialized systems were ideally 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). Linking these deductive classifications to our typical SES, via a nested hierarchy (Fig. 4) allowed us to unpack the diversity of human-nature connectedness dynamics. For example, in Cumming et al.'s typologies, most typical SESs would simply fall into red-loop, industrialized systems, whereas 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 dependence on local natural capital that characterizes green-loop SESs was linked to natural and agricultural systems that showed different levels of biophysical connectedness (from non-industrialized to industrialized), which can have distinct management and sustainability implications.

To our knowledge, our study is the first to apply a nested archetype analysis which brings together inductively, data-driven archetype analyses with deductive analyses for assessing human-nature connectedness. This assessment can also inform other types of experiential and emotional connections of humans with nature (Balázsi et al., 2019), whose understanding might reveal potential for reconnecting society with the biosphere (Folke et al., 2011). In addition, human-nature connectedness research can inform transitional pathways towards the sustainability of SES (Ives et al., 2017), which might be understood as units of management at regional scale (Dorninger et al., 2017). 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 globally recognisable, generic archetypes; 2) generating more potentially comparable and transferable insights across scales and contexts (Sietz et al., 2019); and 3) improving the usefulness and adaptability of archetypes to support territorial planning and resource use management (Hamann et al., 2015; Sietz et al., 2017; Vallejos et al., 2020).

Implications for sustainability and governance challenges

Integrating our analyses of the spatial overlap between typical SESs and SECHs where these types are linked into typologies of human-nature connectedness provided insights to identify major sustainability challenges, such as potential ongoing regime shifts and trajectories towards social-ecological traps (Fig. 5; Appendix 3B, Table B5). Overall, SESs dominated by agricultural areas received the main human pressures. For instance, the intensification of already intensively managed cropping systems on drylands (Fig. 5, 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 dependence on local natural capital. 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 (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 connection with the landscape in these rural areas (Balázsi et al., 2019; Sánchez-Zamora et al., 2014).

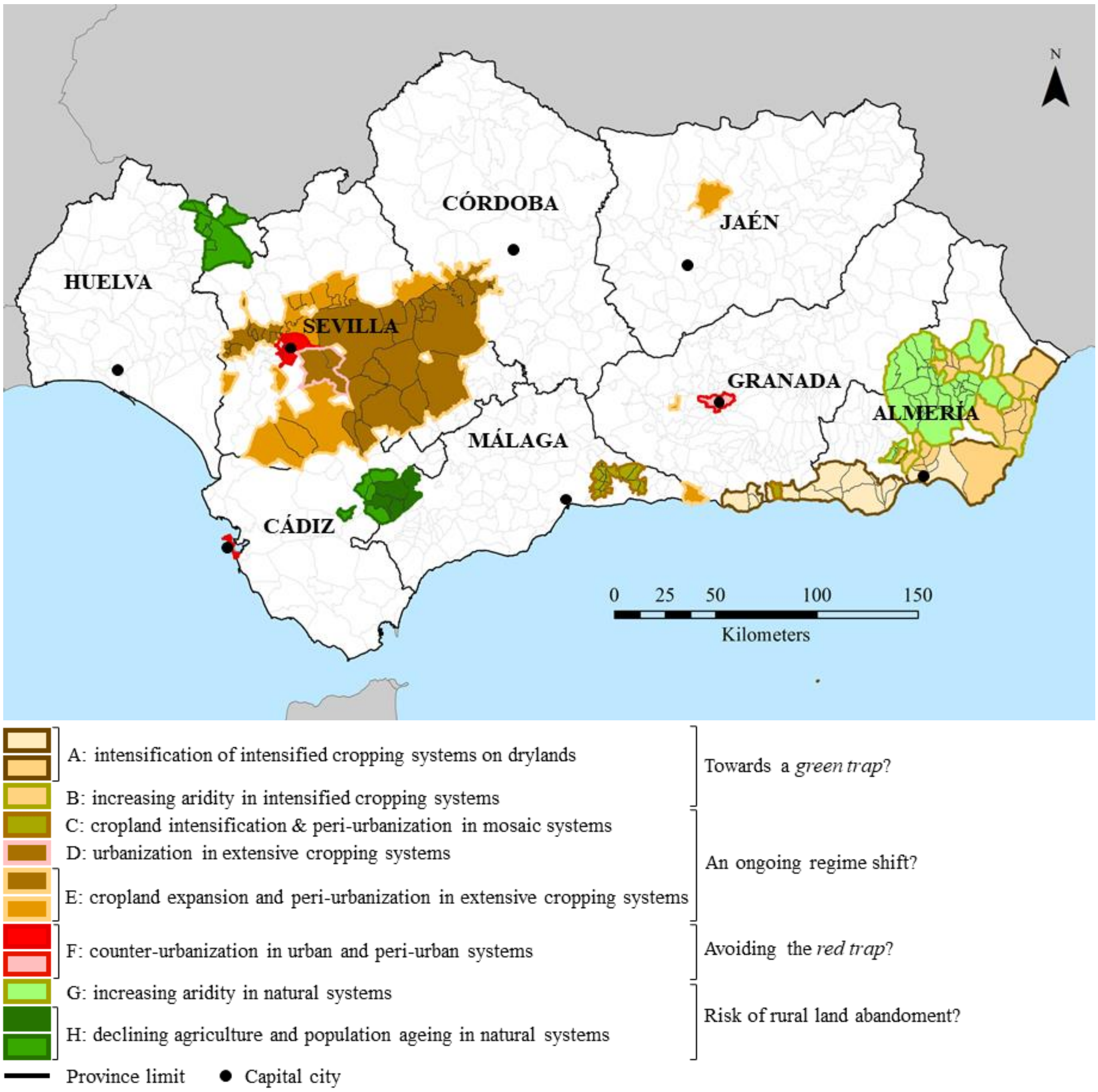

Fig. 5. Spatial patterns of potential sustainability challenges (A-H) based on co-occurring SECHs and SESs. Description of the challenges indicates the typical SECH affecting each SES (please refer to Appendix 3B, Table B5). Background colour for SESs follows the colour code of Fig. 2A, while line colour indicates the specific SECH affecting to each SES, following the colour code of Fig. 2B.

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 et al., 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.

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, organic agricultural production). Finally, 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). We suggest that dealing with these limitations will be important to achieve more comparable outcomes in SES research and thus to upscale empirical knowledge in theorizing sustainability science.

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 structure 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.

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3. DISCUSIÓN GENERAL

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El concepto de sistema socio-ecológico (SSE) proporciona un prisma desde el que analizar los retos que plantea el cambio global, pues permite integrar las complejas interrelaciones que se establecen entre los sistemas humanos y naturales a través de escalas espaciales y temporales anidadas (Liu et al., 2007). Al tratarse de un campo de investigación emergente que se nutre de las ciencias naturales y sociales, los progresos realizados se han construido sobre un cierto pluralismo conceptual y metodológico que está dificultando la comparación de resultados y la síntesis del conocimiento obtenido a través de casos de estudio (Colding & Barthel, 2019; de Vos et al., 2019; Herrero-Jáuregui et al., 2018). Esta tesis doctoral proporciona avances conceptuales y metodológicos para la operacionalización del concepto de SSE que pueden contribuir a desarrollar investigaciones empíricas más comparables y generalizables, así como a potenciar su papel como unidad básica de estudio en ciencias de la sostenibilidad (Balvanera et al., 2017b; Berkes, 2017; Fischer et al., 2015). Concretamente, los resultados obtenidos aportan nuevo conocimiento y perspectivas a dos áreas fundamentales para el progreso de la investigación socio-ecológica: 1) la búsqueda de variables clave para caracterizar SSE; y 2) la cartografía de arquetipos de SSE.

3.1. Hacia las variables esenciales para caracterizar sistemas socio-ecológicos

La investigación a largo plazo de los SSE es un pilar fundamental para orientar políticas de sostenibilidad que den una respuesta integrada a los desafíos medioambientales que surgen de las interacciones humanos-naturaleza (Dick et al., 2018; Mirtl et al., 2018). Para que estas investigaciones contribuyan de forma efectiva al avance del conocimiento sobre SSE y al desarrollo de nuevas teorías en este ámbito, es necesario producir información consistente y comparable a través de casos de estudio a lo largo del tiempo (Cox et al., 2020; Magliocca et al., 2018). Para ello es fundamental disponer de herramientas y protocolos que fomenten un conocimiento común de los factores más importantes para analizar SSE, y permitan ofrecer respuestas coordinadas. En este sentido, los listados de variables de referencia facilitan el uso de un lenguaje común en investigación empírica, y hacen más consistente la forma en la que seleccionamos y medimos variables para caracterizar los SSE (Cox et al., 2020; Ostrom et al., 2009).

Esta tesis doctoral contribuye al conocimiento de las variables más relevantes para la caracterización de SSE mediante dos enfoques complementarios que combinan una evaluación de tipo *top-down*, basada en conocimiento experto (sección 2.1), y una evaluación empírica de tipo *bottom-up*, basada en datos (sección 2.2) (Fig. 1, en *Introducción general*). Así, a través de la evaluación experta se desarrolló un marco global de las variables más relevantes para caracterizar SSE, potencialmente aplicable en cualquier lugar, mientras que la evaluación basada en datos proporcionó un enfoque contexto-específico complementario en el que se identificaron las variables más relevantes para cartografiar los SSE de Andalucía (España). La comparación de los resultados de ambos análisis (en sección 2.2) permitió identificar puntos de sinergia pero también de desacuerdo entre la relevancia de las variables percibida por expertos, y su relevancia empírica para cartografiar SSE a través de distintas escalas (tanto en nuestro caso de estudio en Andalucía como en una selección de los principales estudios de cartografía de SSE a escala local, regional y global). Se identificaron variables claramente relevantes a través de contextos y escalas en las que conocimiento experto y estudios empíricos mostraron coincidencia, y que podrían ser potenciales candidatas a variables socio-ecológicas esenciales (Guerra et al., 2019). También se identificaron variables cuya relevancia podría ser dependiente del contexto o de la escala, así como variables en las que conocimiento experto y empírico no coincidieron (p.ej., variables no consideradas relevantes por expertos, pero muy usadas de facto en cartografía de SSE, y viceversa). En otros casos, la falta de evidencia empírica o de conocimiento experto destacó la necesidad de seguir investigando para determinar la relevancia de algunas variables en la caracterización de SSE. En línea con investigaciones recientes, los resultados de esta tesis evidencian que uno de los actuales desafíos a los que se enfrenta la investigación sobre SSE es identificar qué características y patrones son más generalizables, y cuáles son contexto-específicos (Magliocca et al., 2018; Rocha et al., 2019). En este sentido, uno de los principales retos para el desarrollo de listados de variables esenciales sería integrar tanto atributos relevantes a través de contextos y escalas, como aquellos que reflejen aspectos cuya relevancia sea más contexto-dependiente, organizados en estructuras jerárquicas (Cox et al., 2020; Ostrom, 2009). En general, estos desafíos evidencian la importancia de combinar evaluaciones de expertos con estudios empíricos, tanto desde perspectivas *top-down* (generalizables) como *bottom-up* (contexto-específicas), de cara a identificar variables esenciales para los SSE (Guerra et al., 2019).

3.2. Potenciando la comparabilidad en cartografía de arquetipos de SSE

El análisis de arquetipos ha emergido como una herramienta fundamental de investigación en ciencias de la sostenibilidad para la identificación de tipologías de interacción humanos-naturaleza (p.ej., de sistemas socio-ecológicos) (Oberlack et al., 2019). La cartografía de arquetipos de SSE permite trasladar este concepto al territorio y hacerlo espacialmente explícito, mediante la delimitación de unidades territoriales que comparten características sociales, ecológicas, y de interacción humanos-naturaleza similares (Vallejos et al., 2020). Los mapas de SSE pueden ayudar a enfocar los esfuerzos de investigación hacia lugares con características socio-ecológicas singulares poco estudiadas (Sietz et al., 2019). También pueden servir como base para el desarrollo de una planificación integrada del territorio, ajustada a las particularidades de cada contexto, que contribuya a diseñar nuevas fórmulas hacia escenarios más sostenibles (Sietz et al., 2019). Los arquetipos de SSE han sido cartografiados a través de contextos y escalas espaciales utilizando conjuntos de variables y aproximaciones muy heterogéneas que han dado lugar a múltiples interpretaciones del SSE (Rocha et al., 2020). Por ejemplo, SSE como sistemas de uso del suelo, según el tipo e intensidad de uso del suelo (Asselen & Verburg, 2012; Václavík et al., 2013); como *bundles* de servicios de los ecosistemas, según el patrón de provisión o demanda de servicios de los ecosistemas (Hamann et al., 2015; Quintas-Soriano et al., 2019; Raudsepp-Hearne et al., 2010); o más generalmente, como unidades territoriales de diversa denominación (e.g., antromas, *hotspots* socio-ecológicos, tipos funcionales socio-ecológicos) donde confluyen determinados factores sociales, ecológicos, y/o de interacción socio-ecológica (Alessa et al., 2008; Dressel et al., 2018; Ellis & Ramankutty, 2008; Martín-López et al., 2017; Rocha et al., 2020; Vallejos et al., 2020). Aunque esta diversidad de aproximaciones ha enriquecido el conocimiento sobre los aspectos que determinan la caracterización y configuración espacial de los SSE, la dispersión metodológica y conceptual podría estar obstaculizando la comparación de los resultados obtenidos y la transferencia del conocimiento entre escalas (Balvanera et al., 2017a; de Vos et al., 2019). Los resultados de esta tesis doctoral contribuyen a tres elementos fundamentales para potenciar el papel de la cartografía de SSE como generadora de conocimiento empírico comparable (Fig. 1, en *Introducción general*): 1) la selección de indicadores; 2) la introducción de la componente temporal; y 3) la generalización del conocimiento.

En primer lugar, el marco conceptual y listado de referencia de variables desarrollado en la sección 2.1 de esta tesis proporcionaron una estructura común para orientar la selección de indicadores, organizar la base de datos y caracterizar los SSE identificados empíricamente en las secciones 2.2 y 2.3. Se trata de una estrategia hacia la que convergen los estudios más recientes de cartografía de SSE. Por ejemplo, Dressel et al. (2018) y Rocha et al. (2020)

utilizaron indicadores que vincularon a variables de primer y segundo nivel del marco conceptual del SSE de Ostrom (2009). Por otra parte, Vallejos et al. (2020) seleccionaron indicadores para explicar los principales componentes y dimensiones del funcionamiento socio-ecológico, tomando como soporte el marco conceptual de Resilience Alliance (2007). A través de nuestro marco y listado para caracterizar y cartografiar SSE, construido a partir de conocimiento experto, pretendimos ofrecer un enfoque complementario al de Ostrom, más fácil de operacionalizar, y que diera respuesta a las dificultades reportadas por otros estudios empíricos relacionadas con la ambigüedad y la abstracción de algunas variables (p. ej., Delgado-Serrano & Ramos, 2015; Leslie et al., 2015). Así, nuestro listado de variables, además de estar estructurado jerárquicamente en dimensiones y componentes del funcionamiento socio-ecológico, ofreció un innovador esquema de priorización para las variables basado en la relevancia y consenso asignado por expertos. Dicha priorización potencia la flexibilidad del marco y puede ayudar al investigador a decidir qué es lo importante en un contexto particular (Ostrom, 2009). En general, utilizar marcos conceptuales y listados de referencia de variables como soporte para la cartografía de SSE facilita: 1) trabajar con la complejidad socio-ecológica; 2) contextualizar mejor qué aspectos o variables críticas del SSE son medidos y explicados a partir de los indicadores utilizados; 3) acumular conocimiento a través de estudios empíricos sobre SSE; y 4) orientar la formulación de políticas adaptadas al contexto (Dressel et al., 2018; Rocha et al., 2020).

Por otra parte, la propuesta metodológica planteada en la sección 2.2 facilitó una selección más objetiva de los indicadores más relevantes para cartografiar SSE en el área de estudio. Se trata de una rutina metodológica repetible, basada en datos, que puede contribuir a acumular conocimiento empírico sobre las variables e indicadores que más determinan la configuración espacial de los SSE a través de contextos y escalas. En general, no se han encontrado referencias a que este tipo de análisis hayan sido aplicados por los estudios de cartografía de SSE desarrollados hasta el momento (pero ver Cruces-Pastor et al., 2010), lo que evidencia que la selección de indicadores se ha realizado principalmente de forma deliberada, según el objetivo de la investigación o la disponibilidad concreta de datos. De hecho, estudios recientes destacan la falta de protocolos estándar para la selección o exclusión de variables en casos de estudio empírico, lo que puede derivar en errores relacionados con incluir variables que debemos eliminar (y viceversa), bien porque sean poco relevantes o estén correlacionadas con otras más relevantes, o porque solo representen un grupo sesgado de dimensiones de los SSE (Cox et al., 2020). Por ello, combinar el uso de marcos conceptuales y listados de referencia de variables con análisis empíricos basados en datos podría contribuir a hacer más sistemático y transparente el proceso de selección de indicadores para cartografiar SSE. Conectar indicadores localmente importantes (sección 2.2) con variables clave globales (sección 2.1) favorece escalar el conocimiento obtenido mediante investigación socio-ecológica basada en el lugar y, en definitiva, comparar a través de casos de estudio (Guerra et al., 2019). Esto a su vez favorece generar mapas sensibles a las características del contexto, útiles para la gestión del territorio y formulación de políticas específicas, y cuyo conocimiento pueda ser comparado entre regiones (Rocha et al., 2020).

En segundo lugar, esta tesis utiliza un enfoque novedoso para introducir la componente temporal en la cartografía y caracterización de SSE (sección 2.3). Este enfoque está basado en la identificación de áreas afectadas por procesos de cambio similares (arquetipos de cambio socio-ecológico) y su solapamiento espacial con la distribución actual de los SSE del área de estudio. Los escasos estudios que han cartografiado SSE en el tiempo normalmente han registrado cambios en su distribución espacial. Por ejemplo, Renard et al. (2015) analizaron cambios espaciales en la provisión de *bundles* de servicios de los ecosistemas. Sin embargo, raramente se ha analizado cómo el cambio socio-ecológico afecta a los SSE en sí mismos, por lo que introducir la componente temporal en el análisis de arquetipos debe ser una prioridad (Oberlack et al., 2019). En este sentido, Levers et al. (2018) plantearon una aproximación para identificar los arquetipos de cambio que afectan a los sistemas de uso del suelo del continente europeo. Esta tesis integra por primera vez una perspectiva más holística, pues incorpora las múltiples dimensiones del funcionamiento de los SSE en un análisis espacio-temporal. Se trata de un paso fundamental para representar y explicar la complejidad de los SSE y su dinámica a través de cartografías que reflejen los procesos que los han configurado y que faciliten la planificación del territorio y las políticas públicas hacia escenarios más sostenibles (Hamann et al., 2015; Levers et al., 2018).

En tercer lugar, para potenciar la generalización del conocimiento obtenido a través de la cartografía de SSE, esta tesis desarrolla un análisis anidado de arquetipos que integra las fortalezas de los enfoques inductivo (*bottom-up*) y deductivo (*top-down*) (sección 2.3). Así, se combinó el potencial del enfoque inductivo, basado en datos, para identificar y caracterizar empíricamente los SSE del área de estudio, con el poder interpretativo de los arquetipos deductivos para clasificar los SSE en función de su conectividad humanos-naturaleza (Ives et al., 2017, 2018). De esta manera, los distintos tipos de SSE del área de estudio (naturales, agrícolas, mosaico, urbanos, etc.) fueron contextualizados según su nivel de industrialización y dependencia del capital natural local, siguiendo las clasificaciones deductivas de Dorninger et al. (2017) y Cumming et al. (2014), respectivamente. Integrar ambas perspectivas permitió desarrollar una clasificación anidada que incorporó varios niveles de abstracción (Oberlack et al., 2019), manteniendo la contexto-especificidad de la diversidad regional de SSE a la vez que vinculándola a tipologías genéricas, globalmente reconocibles. En general, la combinación de un análisis espacio-temporal con una clasificación inductiva-deductiva de los SSE facilitó la identificación de los potenciales desafíos de sostenibilidad a los que se enfrenta el área de estudio. Un enfoque de este tipo puede facilitar la transferencia de conocimiento a través de escalas, desde contextos locales a regionales y globales (Rocha et al., 2019; Sietz et al., 2019). Además, esta combinación incrementa el potencial de generalizar y contextualizar casos de estudio particulares para informar estrategias políticas a mayor escala, a la vez que mantiene su utilidad para orientar respuestas de gestión más específicas a escala local (Balvanera et al., 2017a; Fischer et al., 2017; Magliocca et al., 2018; Václavík et al., 2016).

3.3. Líneas futuras de investigación

La consolidación conceptual y metodológica es uno de los principales desafíos para el progreso de la investigación en el ámbito de los SSE (Colding & Barthel, 2019; de Vos et al., 2019), así como para afianzar el papel de este concepto como unidad básica de análisis en ciencias de la sostenibilidad (Berkes, 2017; Colding & Barthel, 2019; Fischer et al., 2015). Conocer el estado del arte en torno a la investigación sobre SSE debe ser un primer paso fundamental. En este sentido, algunos estudios recientes han condensado la trayectoria científica en torno al concepto de SSE en general (p.ej., Colding & Barthel, 2019; Herrero-Jáuregui et al., 2018; Preiser et al., 2018), a las aproximaciones metodológicas aplicadas para su estudio (de Vos et al., 2019), y a los marcos conceptuales desarrollados (Binder et al., 2013; Partelow et al., 2018). Sin embargo, aún no se ha realizado una revisión de la literatura sobre cartografía de SSE, lo que podría ayudar a organizar el conocimiento existente en torno a una de las aproximaciones metodológicas más empleada y con mayor potencial para el avance de la investigación socio-ecológica basada en el lugar (de Vos et al., 2019). Por lo tanto, futuros trabajos de revisión en el ámbito de la cartografía de SSE podrían sintetizar las lecciones aprendidas con relación a: 1) las razones que motivan la cartografía de SSE; 2) contextos y escalas de estudio; 3) marcos conceptuales y/o variables empleadas; 4) metodología aplicada; 5) estimación del número óptimo de SSE; 6) caracterización de los SSE identificados.

A su vez, la sistematización del conocimiento generado puede contribuir a otro de los grandes retos que la investigación socio-ecológica deberá afrontar en los próximos años: la identificación de las variables esenciales de los SSE (Guerra et al., 2019; Lehmann et al., 2020; Reyers et al., 2017). Se trata de un aspecto fundamental para impulsar el desarrollo de protocolos más homogéneos para el seguimiento socio-ecológico a largo plazo (Holzer et al., 2018), así como para generar conocimiento más comparable y generalizable en investigación empírica (Frey, 2017). La evidencia acumulada y criterios ya definidos para otros ámbitos como el clima, la biodiversidad, o los océanos pueden orientar la identificación de variables esenciales para los SSE (Reyers et al., 2017). Sin embargo, la literatura científica en general, y los resultados de esta tesis en particular reflejan que la relevancia de las variables para caracterizar SSE es más contexto-dependiente que en otros ámbitos (Ostrom, 2009). Para abordar este desafío, los listados que se desarrollen deberán ser más flexibles, por ejemplo, estableciendo jerarquías y priorizaciones que permitan integrar variables de relevancia universal, y variables cuya relevancia dependa del contexto (Ostrom, 2009; Rocha et al., 2019). En general, disponer de un listado de variables esenciales para los SSE consensuado por la comunidad científica facilitará un estudio y seguimiento de los SSE más sistemático (Cox et al., 2020; Frey, 2017), y potenciará la interconexión del conocimiento generado a través de contextos y escalas (Balvanera et al., 2017a). Asimismo, facilitará manejar la gran cantidad de datos disponibles en algunos territorios, pero también la escasez de estos en otras zonas en las que sea necesario priorizar los recursos para su obtención (Dressel et al., 2018; Rocha et al., 2020).

Finalmente, las futuras investigaciones también deberán potenciar el papel de los mapas de SSE como herramienta clave para el diseño de medidas de gestión y políticas de desarrollo territorial sostenible. Hasta ahora, la mayoría de las cartografías desarrolladas han constituido pruebas de concepto de diferentes enfoques y metodologías. Sin embargo, también es fundamental potenciar los estudios en los que la cartografía de SSE ayude a responder preguntas de investigación concretas coproducidas con políticos y gestores orientadas a resolver conflictos y desafíos de sostenibilidad en los territorios (López-

Rodríguez et al., 2015). Por ejemplo, Dressel et al. (2018) cartografiaron SSE como medio para entender conflictos relacionados con la gestión de la fauna salvaje. De forma complementaria, es imprescindible impulsar el ensayo de procesos de interfaz ciencia-gestión-sociedad en los que el concepto de SSE sea utilizado como medio para fomentar transiciones hacia escenarios más sostenibles (Becker, 2012; Fischer et al., 2015; López-Rodríguez et al., 2020). Para este fin, el papel de los marcos conceptuales del SSE como objetos frontera para la comunicación entre científicos y gestores ha sido ampliamente discutido y reconocido en investigación transdisciplinar (p.ej., Hertz & Schlüter, 2015; Partelow, 2016). Sin embargo, la utilidad de los mapas de SSE aún no ha sido testada, aunque en determinadas situaciones podrían representar un objeto frontera más tangible e intuitivo que los marcos conceptuales. Por ejemplo, los mapas de SSE pueden contribuir a un mejor entendimiento y visualización de las conexiones entre los sistemas humanos y naturales. En este sentido, los marcos conceptuales y mapas de SSE podrían usarse conjuntamente para fomentar un pensamiento sistémico en procesos de interfaz dedicados a impulsar intervenciones de sostenibilidad transformadoras, por ejemplo, relacionadas con reconectar a la sociedad con la naturaleza (Abson et al., 2017).

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4. CONCLUSIONES GENERALES

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El pluralismo conceptual y metodológico que caracteriza a la investigación sobres sistemas socio-ecológicos (SSE) podría estar dificultando la comparación y generalización del conocimiento obtenido a través de estudios teóricos y empíricos. Esta tesis contribuye a dos ámbitos fundamentales para la construcción de conocimiento comparable en investigación socio-ecológica: 1) la identificación de variables clave para caracterizar SSE; y 2) la cartografía de arquetipos de SSE. Las conclusiones principales de esta tesis en estos dos ámbitos han sido:

1. El desarrollo de listados de referencia de variables es fundamental para impulsar la colección sistemática, coordinada e integradora de datos sobre los SSE, así como para mejorar nuestra capacidad de estudiarlos de forma consistente en el tiempo y en el espacio. Esta tesis contribuye a la identificación de variables clave para la caracterización y seguimiento de los SSE a través de dos enfoques complementarios: 1) uno *top-down*, basado en conocimiento experto y revisiones bibliográficas, que proporcionó una perspectiva general de las variables más relevantes de los SSE mediante un listado de 60 variables priorizadas y estructuradas en un marco conceptual (sección 2.1); y 2) un enfoque *bottom-up*, basado en datos, que proporcionó una perspectiva contexto-específica, y facilita acumular conocimiento empírico sobre variables clave para cartografiar SSE a través de casos de estudio (sección 2.2).

2. La comparación de los resultados de ambos enfoques *top-down* y *bottom-up* (sección 2.2) reveló puntos de sinergia pero también de desacuerdo entre la relevancia de las variables percibida por expertos, y su relevancia empírica para detectar y caracterizar SSE. Identificamos variables potencialmente relevantes a través de contextos y escalas, variables cuya relevancia es más contexto-dependiente, y variables sin acuerdo entre conocimiento empírico y experto para las que serían necesarios más estudios que esclarecieran su papel en la caracterización de SSE. Ante la necesidad actual de desarrollar listados de variables esenciales del SSE, estos resultados evidencian el reto de integrar tanto atributos de relevancia universal como quizá otros cuya relevancia dependa del contexto o escala de análisis.

3. La identificación y cartografía de arquetipos de SSE es una aproximación clave para operacionalizar el concepto de SSE en investigación empírica mediante la delimitación de unidades territoriales con características sociales, ecológicas, y de interacción humanos-naturaleza homogéneas. Esta tesis potencia el papel de la cartografía de SSE como generadora de conocimiento comparable a través de contextos y escalas espacio-temporales, proporcionando avances en tres ámbitos fundamentales: 1) la selección de indicadores; 2) la introducción de la componente temporal; y 3) la generalización del conocimiento.

4. La diversidad en la selección de indicadores para cartografiar SSE ha dado lugar a una gran variedad de enfoques e interpretaciones del SSE que dificultan la generalización del conocimiento obtenido. Para favorecer la comparabilidad, los estudios de cartografía más recientes emplean marcos conceptuales y listados de referencia de variables como lenguaje común para estructurar la base de datos y caracterizar los SSE identificados. Esta tesis ofrece una nueva propuesta de listado de referencia de variables construido a partir de conocimiento experto (sección 2.1). Como principal innovación, el listado se estructuró en un marco conceptual jerárquico formado por dimensiones y componentes del funcionamiento socio-ecológico, ofreciendo además un esquema de priorización de las variables para potenciar un uso más flexible del mismo. Además, esta tesis diseña una rutina metodológica basada en datos (sección 2.2) que permite orientar una selección más objetiva de los indicadores clave para la cartografía de SSE en función del contexto de estudio. La combinación de ambos enfoques facilitó conectar indicadores localmente relevantes con variables y dimensiones del funcionamiento socio-ecológico claves globalmente.

5. Los escasos estudios que han introducido la componente temporal en cartografía de SSE, en general no focalizaron en el análisis de cómo el cambio socio-ecológico afecta a los SSE en sí mismos desde una perspectiva integradora. Esta tesis desarrolla una aproximación para identificar áreas afectadas por procesos de cambio similares (i.e., arquetipos de cambio socio-ecológico), analizando el solapamiento espacial con la distribución de SSE del área de estudio (sección 2.3).

6. Para potenciar la generalización del conocimiento obtenido a través de la cartografía de SSE, esta tesis desarrolla una clasificación anidada de arquetipos que integra las

fortalezas de los enfoques inductivo (*bottom-up*) y deductivo (*top-down*) (sección 2.3). Se combinó el potencial del enfoque inductivo, basado en datos, para identificar y caracterizar empíricamente los SSE, con el poder interpretativo de los arquetipos deductivos. Así, la clasificación resultante facilitó estructurar la complejidad y diversidad socio-ecológica, incorporando diferentes niveles de abstracción que mantuvieron la contexto-especificidad de la diversidad regional de SSE, vinculándola a arquetipos genéricos, globalmente reconocibles.

7. La aplicación de los avances conceptuales y metodológicos propuestos en esta tesis a la identificación, cartografía y caracterización de los arquetipos de SSE de Andalucía (en secciones 2.2 y 2.3), permitió: 1) identificar los indicadores más relevantes para explicar la diversidad de SSE naturales, agrícolas, mosaico y urbanos de la región; 2) detectar los principales tipos de interacción humanos-naturaleza y *trade-offs* socio-ecológicos entre ellos; 3) identificar los principales procesos de cambio socio-ecológico que afectan a los SSE; 4) descubrir un gradiente de conexión humanos-naturaleza a través de los SSE identificados en base a su nivel de industrialización y dependencia del capital natural local; y 5) identificar los potenciales desafíos de sostenibilidad a los que se enfrentan los SSE, debidos a cambios de régimen en curso y trampas socio-ecológicas emergentes.

8. En general, esta tesis contribuye a dos grandes desafíos científicos fundamentales para integrar el enfoque socio-ecológico en el diseño de soluciones para enfrentar los desafíos de sostenibilidad en el Antropoceno: 1) la identificación de variables esenciales para el estudio y seguimiento de los SSE, y 2) el desarrollo de mapas de SSE más útiles, tanto para una gestión del territorio adaptada al contexto, como para informar discursos y estrategias políticas más amplias.

9. Esta tesis apunta varios caminos futuros necesarios para avanzar en la consolidación conceptual y metodológica en el ámbito de los SSE. En concreto, se precisa más investigación para: 1) sentar las bases de la cartografía de SSE mediante la revisión sistemática del conocimiento generado; 2) avanzar en la identificación consensuada de las variables esenciales del SSE; 3) potenciar el papel de la cartografía de SSE como herramienta para dar respuesta a desafíos específicos de sostenibilidad en los territorios; y 4) emplear la cartografía de SSE como objeto frontera en procesos de

interfaz ciencia-gestión-sociedad para visibilizar la conexión entre los sistemas humanos y naturales.

GENERAL CONCLUSIONS

The conceptual and methodological pluralism that characterizes social-ecological system (SES) research could hinder the comparison and generalization of the knowledge obtained through theoretical and empirical studies. This thesis contributes to two fundamental fields to generate comparable knowledge in social-ecological research: 1) the identification of key variables for the study of SESs; and 2) the mapping and characterization of SES archetypes. The main conclusions of this thesis in these two fields have been:

1. The development of reference lists of variables is fundamental to promote systematic, coordinated and integrative collection of data on SESs, as well as to improve our ability to study them consistently over time and space. This thesis contributes to the identification of key variables for the characterization and monitoring of SESs through two complementary approaches: 1) a top-down approach, based on expert knowledge and literature review, which yielded an overview of the most relevant variables of the SES through a list of 60 prioritized variables structured in a conceptual framework (section 2.1); and 2) a bottom- up, data-driven approach, which provided a context-specific perspective, and facilitates accumulating empirical knowledge on key variables to map SESs through case studies (section 2.2).

2. The comparison of the results of both top-down and bottom-up approaches (section 2.2) revealed points of synergy but also of disagreement between the relevance of the variables perceived by experts, and their empirical relevance to detect and characterize SESs. We identified potentially relevant variables through contexts and scales, variables whose relevance is more context-dependent, and variables without agreement between empirical and expert knowledge for which further assessments would be needed. Given the current need to develop lists of essential SES variables, these results show the challenge of integrating both attributes of universal relevance and perhaps others whose relevance depends on the context or scale of analysis.

3. The identification and mapping of SES archetypes is a key approach to operationalize the SES concept in empirical research by delineating territorial units with homogeneous social, ecological, and human-nature interaction characteristics. This thesis enhances the role of SES mapping as producer of

comparable knowledge across contexts and spatio-temporal scales by advancing in three fundamental areas: 1) the selection of indicators; 2) the introduction of the temporal component; and 3) the generalization of knowledge.

4. The diversity in the selection of indicators to map SESs has led to a wide variety of approaches and interpretations of the SES that hampers the generalization of the obtained knowledge. To promote comparability, the most recent mapping studies use conceptual frameworks and reference lists of variables as a common language to structure the database and characterize the identified SESs. This thesis provides a new reference list of variables built from expert knowledge (section 2.1). As the main innovation, the list was embedded in a hierarchical conceptual framework structured in dimensions and components of social-ecological functioning, and offered a prioritization scheme for the variables to promote a flexible use of the list. In addition, this thesis proposes a data-driven methodological routine (section 2.2) to guide a more objective selection of key indicators for SES mapping depending on the studied context. Combining both approaches facilitated connecting locally relevant indicators with globally key variables and dimensions of social-ecological functioning.

5. The few studies that have introduced the temporal component in SES mapping generally did not focus on analyzing how social-ecological change affects SESs themselves from an integrative perspective. This thesis develops an approach to identify areas affected by similar change processes (i.e., social-ecological change archetypes), and assesses the spatial overlap with the distribution of SESs in the study area (section 2.3).

6. To enhance the generalization of knowledge obtained through SES mapping, this thesis develops a nested archetype classification that integrates the strengths of inductive (bottom-up) and deductive (top-down) approaches (section 2.3). The potential of the inductive, data-driven approach to empirically identify and characterize SESs was combined with the interpretive power of deductive archetypes. Thus, the resulting classification facilitated structuring the social-ecological complexity and diversity, by incorporating different levels of abstraction that keep the context-specificity of regional SES diversity, while linking to globally recognizable, generic archetypes.

7. The application of the conceptual and methodological advances proposed in this thesis to the identification, mapping and characterization of the SES archetypes of Andalusia (in sections 2.2 and 2.3), allowed to: 1) identify the most relevant indicators to explain the diversity of natural, agricultural, mosaic and urban SESs of the region; 2) detect the main types of human-nature interaction and social-ecological trade-offs among them; 3) identify the main social-ecological change processes affecting the SESs; 4) discover a gradient of human-nature connectedness through the identified SESs, based on their level of industrialization and dependence on local natural capital; and 5) identify the potential sustainability challenges of SESs, linked to ongoing regime shifts and emerging social-ecological traps.

8. In general, this thesis contributes to two major research challenges that are fundamental to integrate the social-ecological approach in the design of solutions to face the sustainability challenges in the Anthropocene: 1) the identification of essential variables for the study and monitoring of SESs, and 2) the development of useful SES maps, both for a context-specific territorial management, and for informing broader policy discourses and strategies.

9. This thesis highlights future pathways for advancing in the conceptual and methodological consolidation in the SES field. Specifically, more research is needed to: 1) lay the foundations for SES mapping through systematic review of generated knowledge; 2) advance in the consensual identification of essential SES variables; 3) enhance the role of SES mapping as a tool to answer specific sustainability challenges in territories; and 4) use SES maps as boundary objects in science-policy-society interface processes to raise awareness of the connection between human and natural systems.

APÉNDICES

Apéndices del resultado 2.1

Appendix 1A. List of key references used for identifying variables and dimensions for characterizing the social-ecological system (SES).

Key references on SES conceptual frameworks:

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Appendix 1B. Workshop participants

List of participants in workshop 1 - *"Capturing the functioning of social-ecological systems"*

Venue: University of Granada (Spain)

Dates: 18th – 20th November 2015

Surname / name	Institution	Area of expertise
Alcaraz-Segura, Domingo	Universidad de Granada (Spain)	Remote sensing, ecosystem ecology, conservation biology
Blanco-Sacristán, Javier	Università degli Studi di Milano-Bicocca (Italy)	Remote sensing, ecosystem functioning
Berbery, Hugo	University of Maryland (USA)	Land surface-atmosphere interactions, climate system, water and energy budgets
Cabello, Javier	Universidad de Almería (Spain)	Sustainability, ecology and conservation, ecosystem functions and services
Castro, Antonio	Universidad de Almería (Spain)	Human-environment relationships, sustainability, social-ecological systems
Epstein, Howard	University of Virginia (USA)	Ecosystem functioning, vegetation dynamics, climate change, carbon cycling, carbon-water interactions, disturbances regime
Fernández, Néstor	German Centre for Integrative Biodiversity Research – iDiv (Germany)	Ecosystem functioning, biodiversity and conservation, ecological modelling, remote sensing
Jobbágy, Esteban	Universidad Nacional de San Luis (Argentina)	Ecosystem ecology, human control of ecosystem processes, ecohydrology
Lourenço, Patricia	Universidade de Évora (Portugal)	Ecosystem functioning, remote sensing, conservation biology
Oyonarte, Cecilio	Universidad de Almería (Spain)	Soil science, geochemistry, carbon dynamics, climate change
Pacheco-Romero, Manuel	Universidad de Almería (Spain)	Social-ecological systems, sustainability

Paruelo, José	Universidad de Buenos Aires (Argentina)	Ecosystem structure and functioning, ecological modelling, remote sensing, ecosystem services
Peñas, Julio	Universidad de Granada (Spain)	Conservation biology, biodiversity, plant ecology, biogeography
Pérez-Cazorla, Beatriz	Universidad de Almería (Spain)	Ecosystem functioning, remote sensing, conservation biology
Requena-Mullor, Juan Miguel	Boise State University (USA)	Ecological modelling, conservation biology, remote sensing
Reyes, Andrés	Universidad de Almería (Spain)	Ecosystem functioning, remote sensing, conservation biology

List of participants in Workshop 2 - *"Towards the identification of Social-Ecological Functional Types"*

Venue: University of Buenos Aires (Argentina)

Dates: 6th - 11th February 2017

Surname / name	Institution	Area of expertise
Aguiar, Sebastián	Universidad de Buenos Aires (Argentina)	Natural resource management, territorial planning, political ecology, sustainability
Alcaraz-Segura, Domingo	Universidad de Granada (Spain)	Remote sensing, ecosystem ecology, conservation biology
Bagnato, Camilo	Universidad de Buenos Aires (Argentina)	Ecosystem functioning, remote sensing, territorial planning
Blanco-Sacristán, Javier	Università degli Studi di Milano-Bicocca (Italy)	Remote sensing, ecosystem functioning
Berbery, Hugo	University of Maryland (USA)	Land surface-atmosphere interactions, climate system, water and energy budgets

Cabello, Javier	Universidad de Almería (Spain)	Sustainability, ecology and conservation, ecosystem functions and services
Epstein, Howard	University of Virginia (USA)	Ecosystem functioning, vegetation dynamics, climate change, carbon cycling, carbon-water interactions, disturbances regime
Fernández, Néstor	German Centre for Integrative Biodiversity Research – iDiv (Germany)	Ecosystem functioning, biodiversity and conservation, ecological modelling, remote sensing
Gallego, Federico	Universidad de la República de Uruguay (Uruguay)	Sustainability, natural resource management, social-ecological systems, ecosystem services, territorial planning
Jobbágy, Esteban	Universidad Nacional de San Luis (Argentina)	Ecosystem ecology, human control of ecosystem processes, ecohydrology
Pacheco-Romero, Manuel	Universidad de Almería (Spain)	Social-ecological systems, sustainability
Paruelo, José	Universidad de Buenos Aires (Argentina)	Ecosystem structure and functioning, ecological modelling, remote sensing, ecosystem services
Peñas, Julio	Universidad de Granada (Spain)	Conservation biology, biodiversity, plant ecology, biogeography
Pérez-Cazorla, Beatriz	Universidad de Almería (Spain)	Ecosystem functioning, remote sensing, conservation biology
Piñeiro, Gervasio	Universidad de Buenos Aires (Argentina)	Biodiversity, ecosystem ecology, sustainability, natural resource management
Vallejos, María	Universidad de Buenos Aires (Argentina)	Sustainability, natural resource management, social-ecological systems, ecosystem services, territorial planning

Appendix 1C. Preliminary online survey

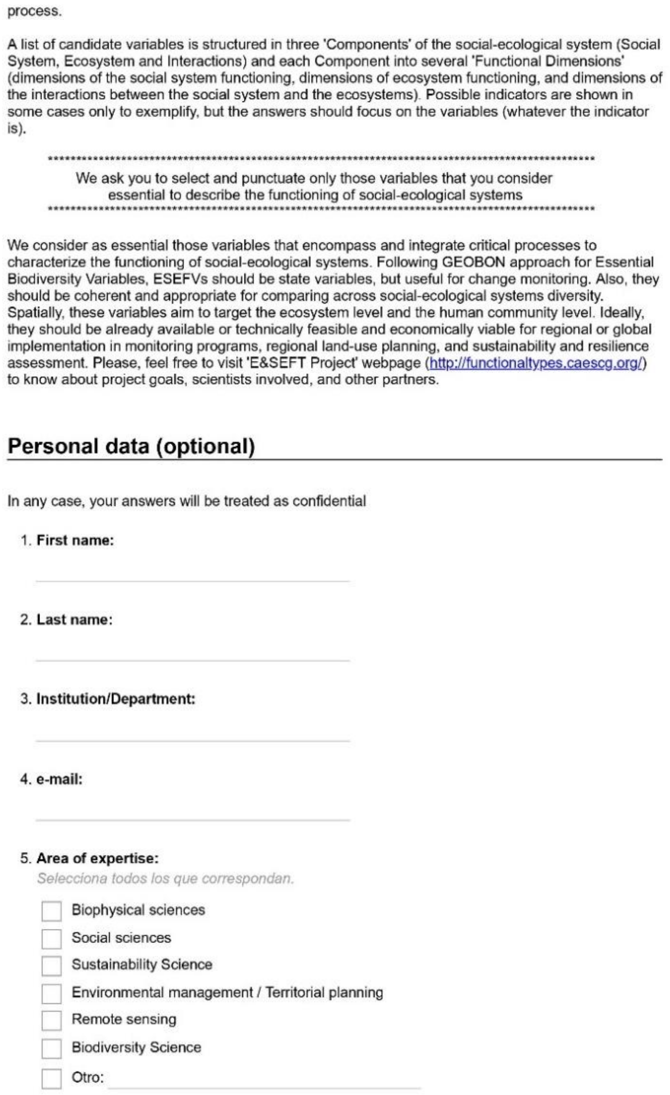
Essential variables to describe the functioning of Social-Ecological Systems

Participating Institutions

UBA Universidad de Buenos Aires *Argentina virtus robur et studium*
Universidad de Almería
Universidad Nacional de San Luis
iDiv German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig
Universidad de Granada
University of Maryland
CSIC Spanish Council of Research
University of Virginia
Idaho State University

Introduction

We aim to integrate biophysical and social processes to produce a functional characterization and mapping of social-ecological systems at the regional scale and landscape level. This survey aims to agree on a set of 'Essential Social-Ecological Functional Variables' (ESEFVs) to be used in such process.



A list of candidate variables is structured in three 'Components' of the social-ecological system (Social System, Ecosystem and Interactions) and each Component into several 'Functional Dimensions' (dimensions of the social system functioning, dimensions of ecosystem functioning, and dimensions of the interactions between the social system and the ecosystems). Possible indicators are shown in some cases only to exemplify, but the answers should focus on the variables (whatever the indicator is).

****

We ask you to select and punctuate only those variables that you consider essential to describe the functioning of social-ecological systems

****

We consider as essential those variables that encompass and integrate critical processes to characterize the functioning of social-ecological systems. Following GEOBON approach for Essential Biodiversity Variables, ESEFVs should be state variables, but useful for change monitoring. Also, they should be coherent and appropriate for comparing across social-ecological systems diversity. Spatially, these variables aim to target the ecosystem level and the human community level. Ideally, they should be already available or technically feasible and economically viable for regional or global implementation in monitoring programs, regional land-use planning, and sustainability and resilience assessment. Please, feel free to visit 'E&SEFT Project' webpage (http://functionaltypes.caescg.org/) to know about project goals, scientists involved, and other partners.

Personal data (optional)

In any case, your answers will be treated as confidential

1. **First name:**

2. **Last name:**

3. **Institution/Department:**

4. **e-mail:**

5. **Area of expertise:**

Selecciona todos los que correspondan.

☐ Biophysical sciences
☐ Social sciences
☐ Sustainability Science
☐ Environmental management / Territorial planning
☐ Remote sensing
☐ Biodiversity Science
☐ Otro: ____________

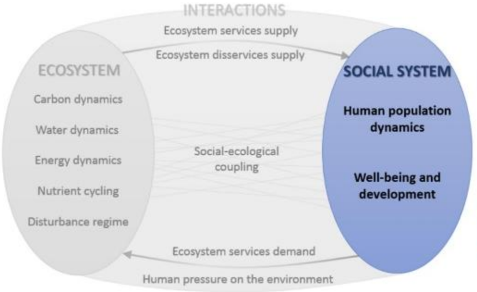
6. **Tick if you want to be acknowledged in derived publications:**
Selecciona todos los que correspondan.

☐ Yes, include my name in the acknowledgments

7. **Tick if you want to receive the results of this study:**
Selecciona todos los que correspondan.

☐ Yes, send to me the results of this study

COMPONENT 1. SOCIAL SYSTEM



Dimension 1a. Human population dynamics

(You are in: Component 1. Social System)

8. **In your opinion, which variables that describe human population dynamics are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Population size	○	○	○	○	○	○
Population density	○	○	○	○	○	○
Population distribution (e.g.: % rural population vs. % urban population)	○	○	○	○	○	○
Age structure (e.g.: median age, population ageing index)	○	○	○	○	○	○
Sex Ratio	○	○	○	○	○	○
Human migrations (e.g.: % of inmigrants/emigrants in a population)	○	○	○	○	○	○

9. **Would you add/modify any variable of human population dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 1b. Well-being and development

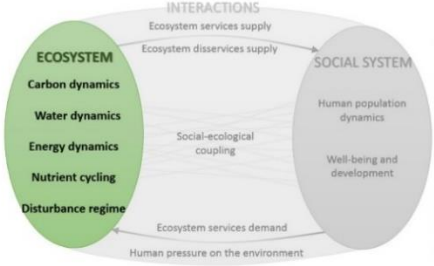
(You are in: Component 1. Social System)

10. **In your opinion, which variables that describe human well-being and development are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Life expectancy (e.g.: life expectancy at birth)	○	○	○	○	○	○
Mortality (e.g.: infant mortality rate)	○	○	○	○	○	○
Access to drinking water (e.g.: distance to drinking water)	○	○	○	○	○	○
Electricity access	○	○	○	○	○	○
Water sanitation (e.g.: % of houses using improved sanitation facilities)	○	○	○	○	○	○
Overcrowding (e.g.: people/ home)	○	○	○	○	○	○
Employment (e.g.: economically active population)	○	○	○	○	○	○
Economic level of the population (e.g.: income per house/ per capita)	○	○	○	○	○	○
Educational level of the population (e.g.: illiteracy rate, % of population with higher education, school enrolment rate, out of school rate for adolescents)	○	○	○	○	○	○
Social equality (e.g.: wealth distribution, women participation in goverment, women literacy rate)	○	○	○	○	○	○
Institutional diversity	○	○	○	○	○	○
Access to internet	○	○	○	○	○	○
Environmental quality (e.g.: air, water and soil pollution levels)	○	○	○	○	○	○
Land protection (% of protected area)	○	○	○	○	○	○

11. **Would you add/modify any variable of social well-being and development to better describe social-ecological systems functioning? Please specify:**

COMPONENT 2. ECOSYSTEM



Dimension 2a. Carbon dynamics

(You are in: Component 2. Ecosystem)

12. **Do you consider Net Primary Productivity as essential to characterize social-ecological systems functioning?**

Please, punctuate this variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Net Primary Productivity	○	○	○	○	○	○

13. **Would you add/modify any variable of carbon dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 2b. Water dynamics

(You are in: Component 2. Ecosystem)

14. **Do you consider evapotranspiration as essential to characterize social-ecological systems functioning?**

Please, punctuate this variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Evapotranspiration	○	○	○	○	○	○

15. **Would you add/modify any variable of water dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 2c. Energy dynamics

(You are in: Component 2. Ecosystem)

16. **In your opinion, which variables that describe energy dynamics are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Land surface energy balance	○	○	○	○	○	○
Land surface temperature	○	○	○	○	○	○
Albedo	○	○	○	○	○	○

17. **Would you add/modify any variable of energy dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 2d. Nutrient cycling

(You are in: Component 2. Ecosystem)

18. **In your opinion, which variables that describe nutrient cycling are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Nitrogen cycling	○	○	○	○	○	○
Phosphorus cycling	○	○	○	○	○	○

19. **Would you add/modify any variable of nutrient cycling to better describe social-ecological systems functioning? Please specify:**

Dimension 2e. Disturbance regime

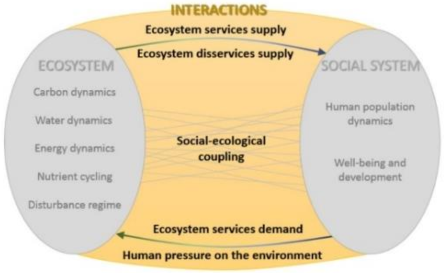
(You are in: Component 2. Ecosystem)

20. **In your opinion, which variables that describe disturance regime are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Fire occurrence	○	○	○	○	○	○
Drought occurrence	○	○	○	○	○	○

21. **Would you add/modify any variable of disturbance regime to better describe social-ecological systems functioning? Please specify:**

COMPONENT 3. INTERACTIONS

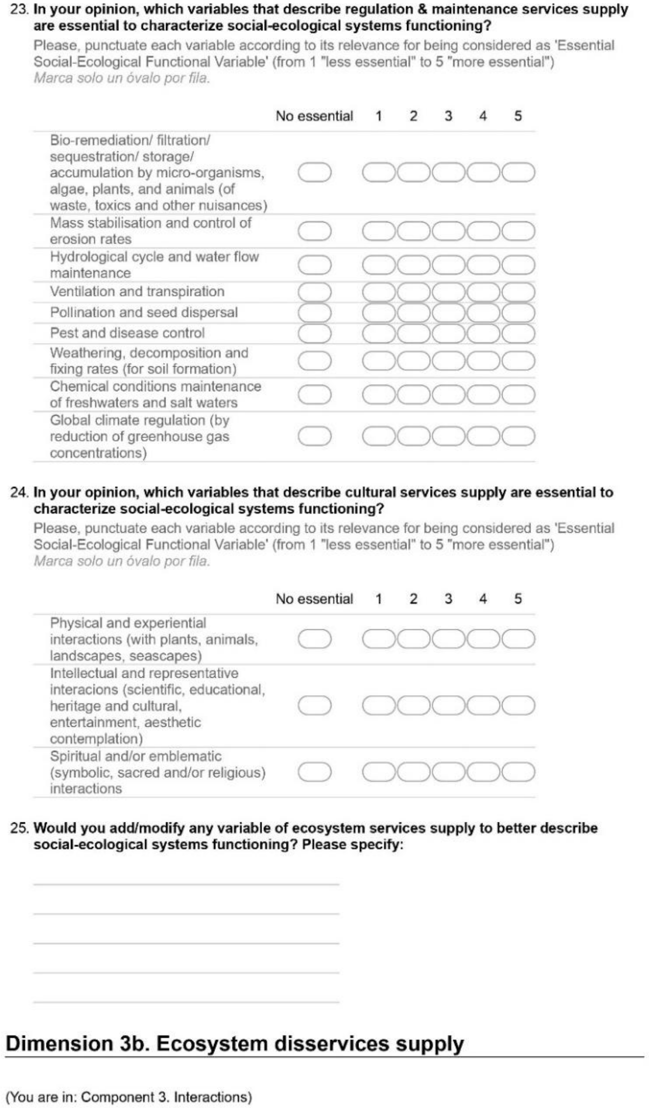


Dimension 3a. Ecosystem services supply

(You are in: Component 3. Interactions)

22. **In your opinion, which variables that describe provisioning services supply are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Agricultural production	○	○	○	○	○	○
Livestock production	○	○	○	○	○	○
Wild plants, algae and their outputs for food	○	○	○	○	○	○
Wild animals and their outputs for food	○	○	○	○	○	○
Surface and ground water sources for drinking	○	○	○	○	○	○
Surface and ground water sources for non-drinking purposes	○	○	○	○	○	○
Fibres and other materials from plants, algae and animals for direct use or processing	○	○	○	○	○	○
Biomass-based energy sources	○	○	○	○	○	○



23. In your opinion, which variables that describe regulation & maintenance services supply are essential to characterize social-ecological systems functioning?

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Bio-remediation/ filtration/ sequestration/ storage/ accumulation by micro-organisms, algae, plants, and animals (of waste, toxics and other nuisances)	○	○	○	○	○	○
Mass stabilisation and control of erosion rates	○	○	○	○	○	○
Hydrological cycle and water flow maintenance	○	○	○	○	○	○
Ventilation and transpiration	○	○	○	○	○	○
Pollination and seed dispersal	○	○	○	○	○	○
Pest and disease control	○	○	○	○	○	○
Weathering, decomposition and fixing rates (for soil formation)	○	○	○	○	○	○
Chemical conditions maintenance of freshwaters and salt waters	○	○	○	○	○	○
Global climate regulation (by reduction of greenhouse gas concentrations)	○	○	○	○	○	○

24. In your opinion, which variables that describe cultural services supply are essential to characterize social-ecological systems functioning?

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

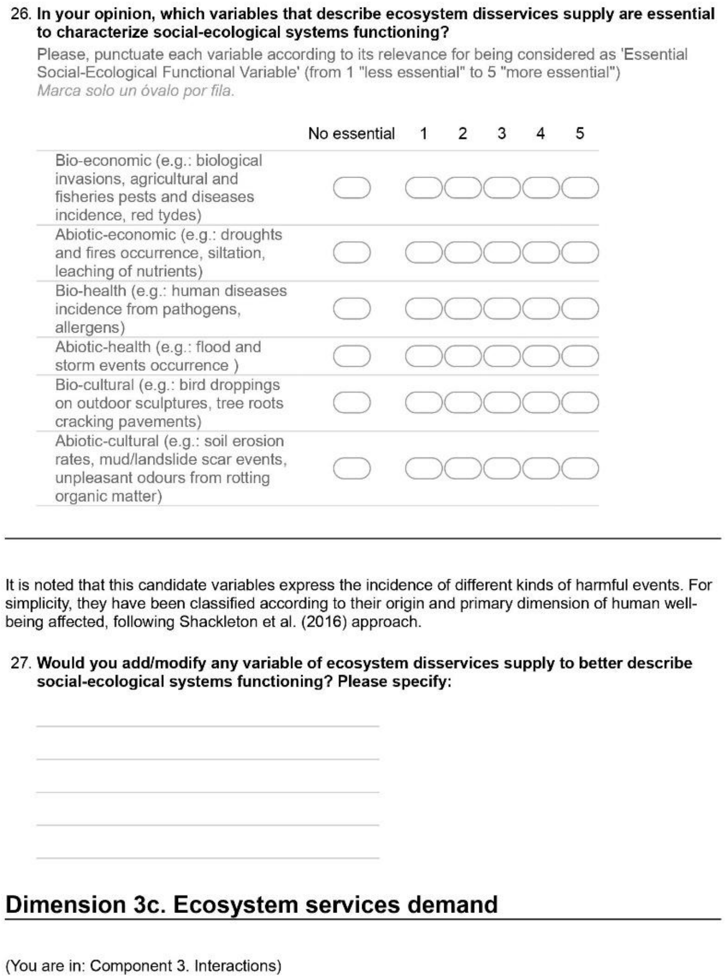
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Physical and experiential interactions (with plants, animals, landscapes, seascapes)	○	○	○	○	○	○
Intellectual and representative interacions (scientific, educational, heritage and cultural, entertainment, aesthetic contemplation)	○	○	○	○	○	○
Spiritual and/or emblematic (symbolic, sacred and/or religious) interactions	○	○	○	○	○	○

25. Would you add/modify any variable of ecosystem services supply to better describe social-ecological systems functioning? Please specify:

Dimension 3b. Ecosystem disservices supply

(You are in: Component 3. Interactions)



26. In your opinion, which variables that describe ecosystem disservices supply are essential to characterize social-ecological systems functioning?

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

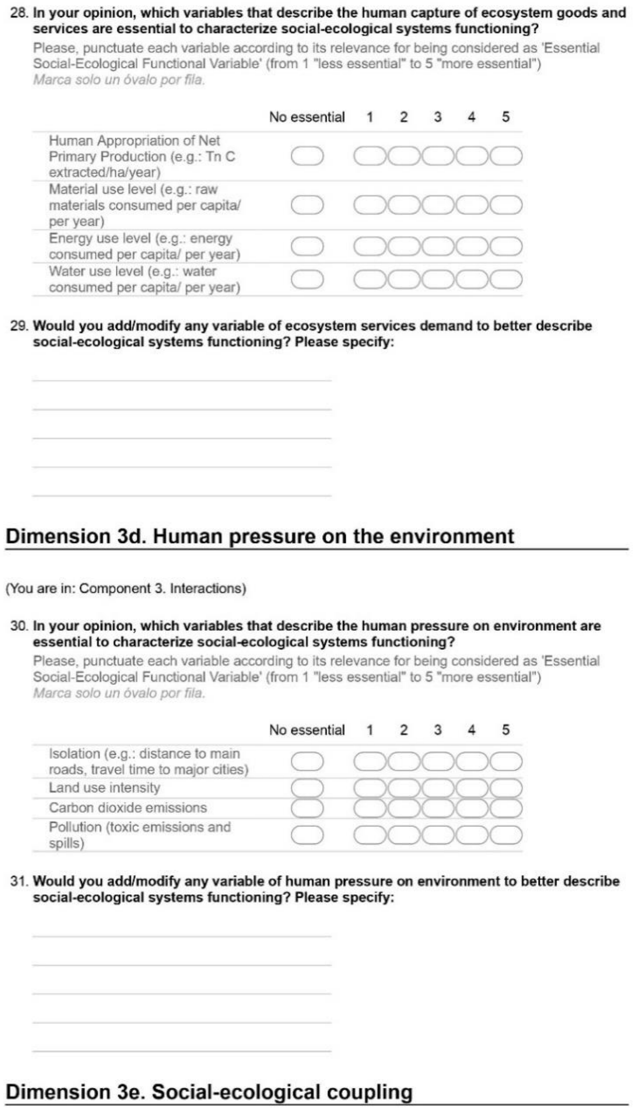
	No essential	1	2	3	4	5
Bio-economic (e.g.: biological invasions, agricultural and fisheries pests and diseases incidence, red tydes)	○	○	○	○	○	○
Abiotic-economic (e.g.: droughts and fires occurrence, siltation, leaching of nutrients)	○	○	○	○	○	○
Bio-health (e.g.: human diseases incidence from pathogens, allergens)	○	○	○	○	○	○
Abiotic-health (e.g.: flood and storm events occurrence)	○	○	○	○	○	○
Bio-cultural (e.g.: bird droppings on outdoor sculptures, tree roots cracking pavements)	○	○	○	○	○	○
Abiotic-cultural (e.g.: soil erosion rates, mud/landslide scar events, unpleasant odours from rotting organic matter)	○	○	○	○	○	○

It is noted that this candidate variables express the incidence of different kinds of harmful events. For simplicity, they have been classified according to their origin and primary dimension of human well-being affected, following Shackleton et al. (2016) approach.

27. Would you add/modify any variable of ecosystem disservices supply to better describe social-ecological systems functioning? Please specify:

Dimension 3c. Ecosystem services demand

(You are in: Component 3. Interactions)



28. In your opinion, which variables that describe the human capture of ecosystem goods and services are essential to characterize social-ecological systems functioning?

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Human Appropriation of Net Primary Production (e.g.: Tn C extracted/ha/year)	○	○	○	○	○	○
Material use level (e.g.: raw materials consumed per capita/ per year)	○	○	○	○	○	○
Energy use level (e.g.: energy consumed per capita/ per year)	○	○	○	○	○	○
Water use level (e.g.: water consumed per capita/ per year)	○	○	○	○	○	○

29. Would you add/modify any variable of ecosystem services demand to better describe social-ecological systems functioning? Please specify:

Dimension 3d. Human pressure on the environment

(You are in: Component 3. Interactions)

30. In your opinion, which variables that describe the human pressure on environment are essential to characterize social-ecological systems functioning?

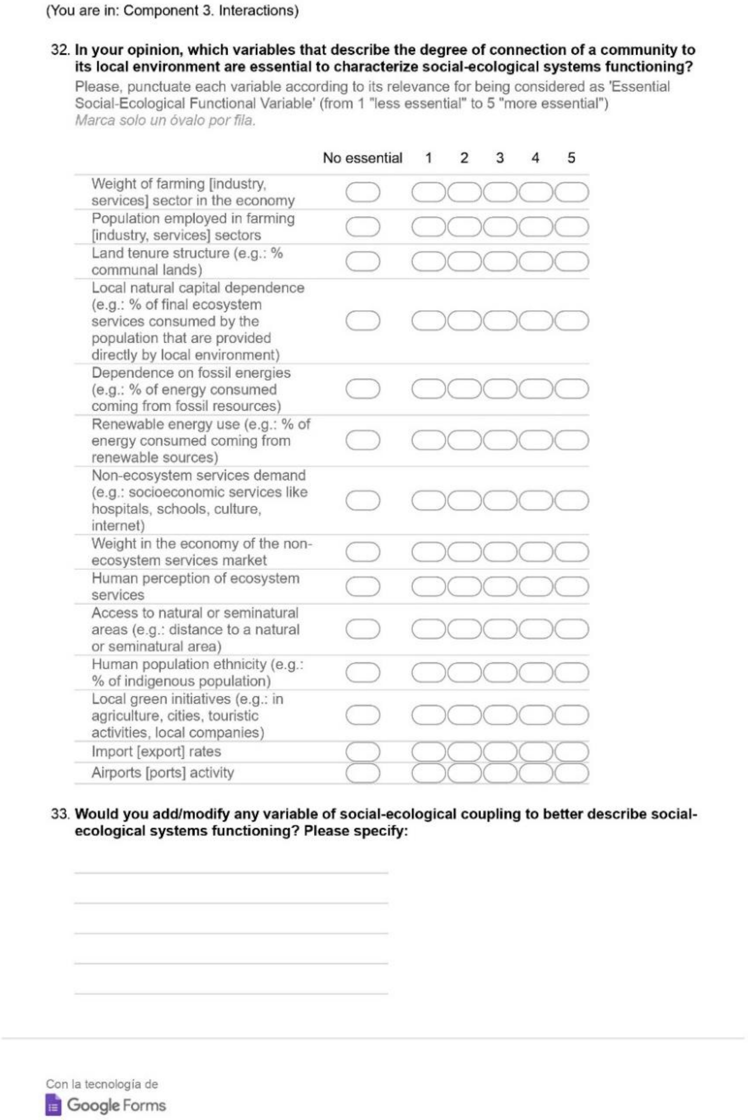
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Isolation (e.g.: distance to main roads, travel time to major cities)	○	○	○	○	○	○
Land use intensity	○	○	○	○	○	○
Carbon dioxide emissions	○	○	○	○	○	○
Pollution (toxic emissions and spills)	○	○	○	○	○	○

31. Would you add/modify any variable of human pressure on environment to better describe social-ecological systems functioning? Please specify:

Dimension 3e. Social-ecological coupling



(You are in: Component 3. Interactions)

32. In your opinion, which variables that describe the degree of connection of a community to its local environment are essential to characterize social-ecological systems functioning?

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Weight of farming [industry, services] sector in the economy	○	○	○	○	○	○
Population employed in farming [industry, services] sectors	○	○	○	○	○	○
Land tenure structure (e.g.: % communal lands)	○	○	○	○	○	○
Local natural capital dependence (e.g.: % of final ecosystem services consumed by the population that are provided directly by local environment)	○	○	○	○	○	○
Dependence on fossil energies (e.g.: % of energy consumed coming from fossil resources)	○	○	○	○	○	○
Renewable energy use (e.g.: % of energy consumed coming from renewable sources)	○	○	○	○	○	○
Non-ecosystem services demand (e.g.: socioeconomic services like hospitals, schools, culture, internet)	○	○	○	○	○	○
Weight in the economy of the non-ecosystem services market	○	○	○	○	○	○
Human perception of ecosystem services	○	○	○	○	○	○
Access to natural or seminatural areas (e.g.: distance to a natural or seminatural area)	○	○	○	○	○	○
Human population ethnicity (e.g.: % of indigenous population)	○	○	○	○	○	○
Local green initiatives (e.g.: in agriculture, cities, touristic activities, local companies)	○	○	○	○	○	○
Import [export] rates	○	○	○	○	○	○
Airports [ports] activity	○	○	○	○	○	○

33. Would you add/modify any variable of social-ecological coupling to better describe social-ecological systems functioning? Please specify:

Con la tecnología de

Google Forms

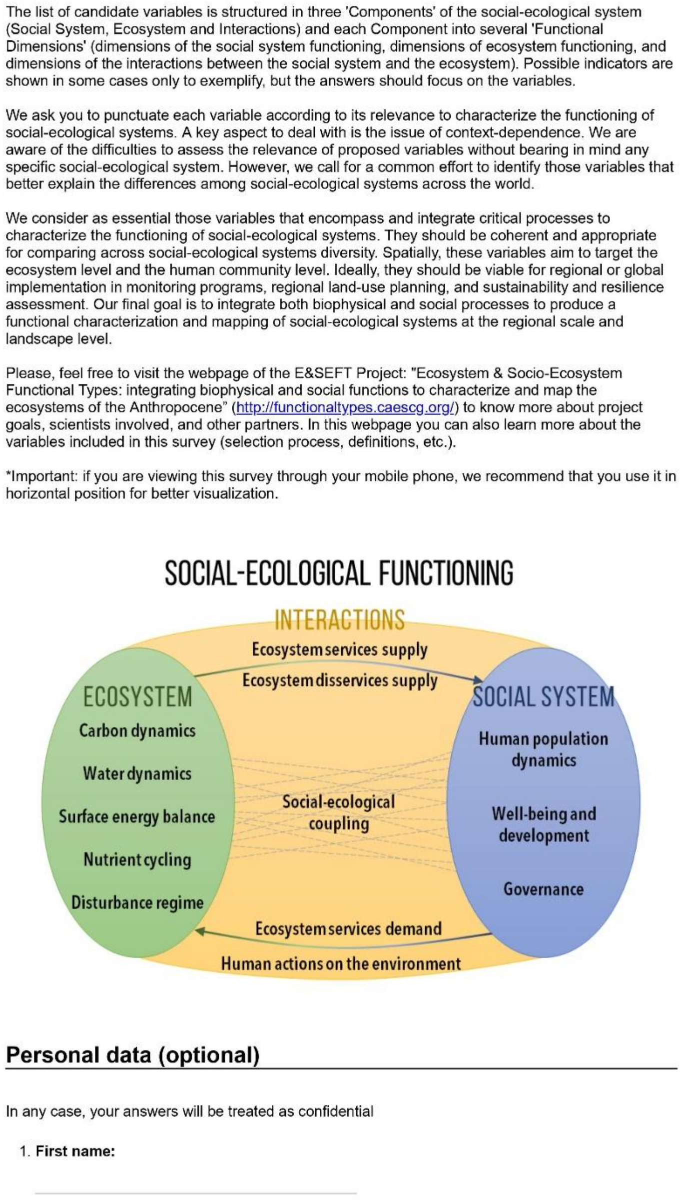
Appendix 1D. Final online survey

Essential variables to characterize the functioning of Social-Ecological Systems

Participating Institutions

Introduction

This survey aims to collect expert opinions and knowledge about key variables to characterize social-ecological systems functioning.



The list of candidate variables is structured in three 'Components' of the social-ecological system (Social System, Ecosystem and Interactions) and each Component into several 'Functional Dimensions' (dimensions of the social system functioning, dimensions of ecosystem functioning, and dimensions of the interactions between the social system and the ecosystem). Possible indicators are shown in some cases only to exemplify, but the answers should focus on the variables.

We ask you to punctuate each variable according to its relevance to characterize the functioning of social-ecological systems. A key aspect to deal with is the issue of context-dependence. We are aware of the difficulties to assess the relevance of proposed variables without bearing in mind any specific social-ecological system. However, we call for a common effort to identify those variables that better explain the differences among social-ecological systems across the world.

We consider as essential those variables that encompass and integrate critical processes to characterize the functioning of social-ecological systems. They should be coherent and appropriate for comparing across social-ecological systems diversity. Spatially, these variables aim to target the ecosystem level and the human community level. Ideally, they should be viable for regional or global implementation in monitoring programs, regional land-use planning, and sustainability and resilience assessment. Our final goal is to integrate both biophysical and social processes to produce a functional characterization and mapping of social-ecological systems at the regional scale and landscape level.

Please, feel free to visit the webpage of the E&SEFT Project: "Ecosystem & Socio-Ecosystem Functional Types: integrating biophysical and social functions to characterize and map the ecosystems of the Anthropocene" (http://functionaltypes.caescg.org/) to know more about project goals, scientists involved, and other partners. In this webpage you can also learn more about the variables included in this survey (selection process, definitions, etc.).

*Important: if you are viewing this survey through your mobile phone, we recommend that you use it in horizontal position for better visualization.

Personal data (optional)

In any case, your answers will be treated as confidential

1. **First name:**

2. **Last name:**

3. **Institution/Department:**

4. **e-mail:**

5. **Area of expertise:**

Selecciona todos los que correspondan.

- ☐ Biophysical sciences
- ☐ Social sciences
- ☐ Sustainability Science
- ☐ Environmental management / Territorial planning
- ☐ Remote sensing
- ☐ Biodiversity Science
- ☐ Otro:

6. **Tick if you want to be acknowledged in derived publications:**

Selecciona todos los que correspondan.

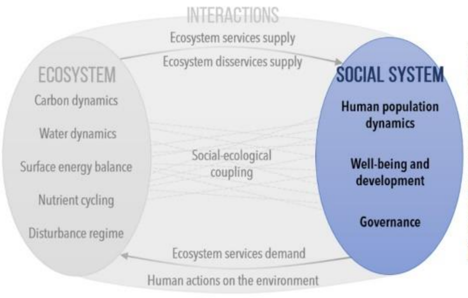
- ☐ Yes, include my name in the acknowledgments

7. **Tick if you want to receive the results of this study:**

Selecciona todos los que correspondan.

- ☐ Yes, send to me the results of this study

COMPONENT 1. SOCIAL SYSTEM



Dimension 1a. Human population dynamics

(You are in: Component 1. Social System)

8. **In your opinion, which variables that describe human population dynamics are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

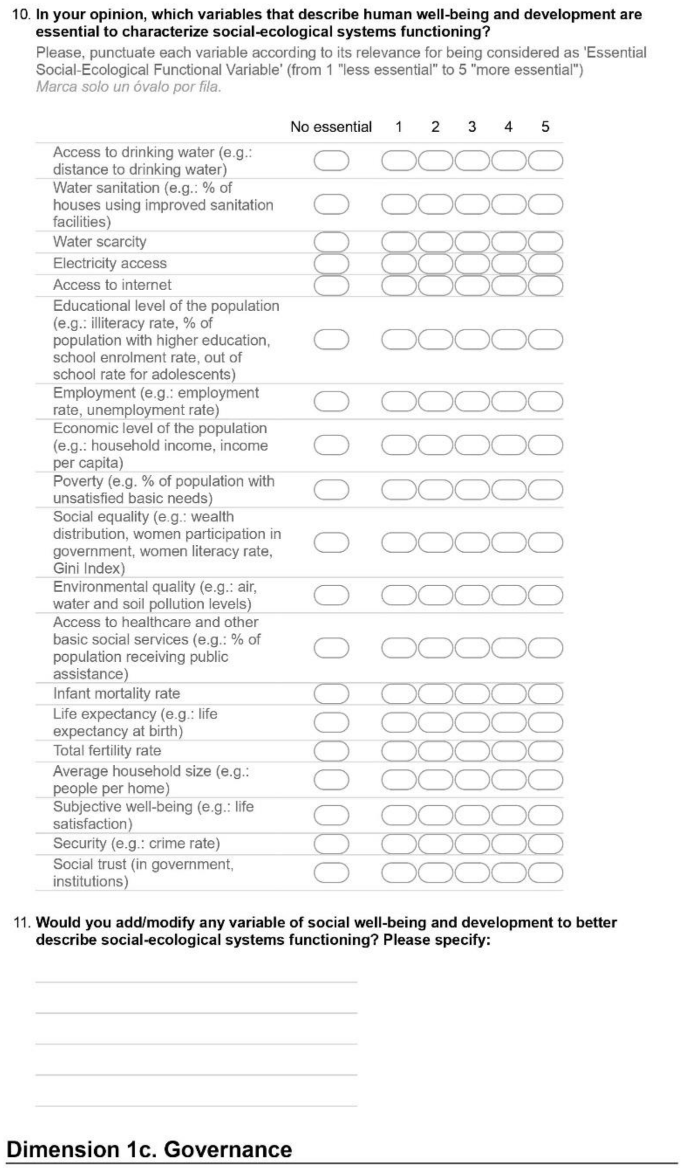
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Population density	○	○	○	○	○	○
Population distribution (e.g.: % rural population vs. % urban population)	○	○	○	○	○	○
Population size	○	○	○	○	○	○
Human migrations (e.g.: ratio of inmigrantion/emigration)	○	○	○	○	○	○
Population growth rate by natural increase	○	○	○	○	○	○
Population growth rate by inmigration	○	○	○	○	○	○
Age structure (e.g.: median age, population ageing index, dependency ratio)	○	○	○	○	○	○
Sex Ratio	○	○	○	○	○	○

9. **Would you add/modify any variable of human population dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 1b. Well-being and development

(You are in: Component 1. Social System)



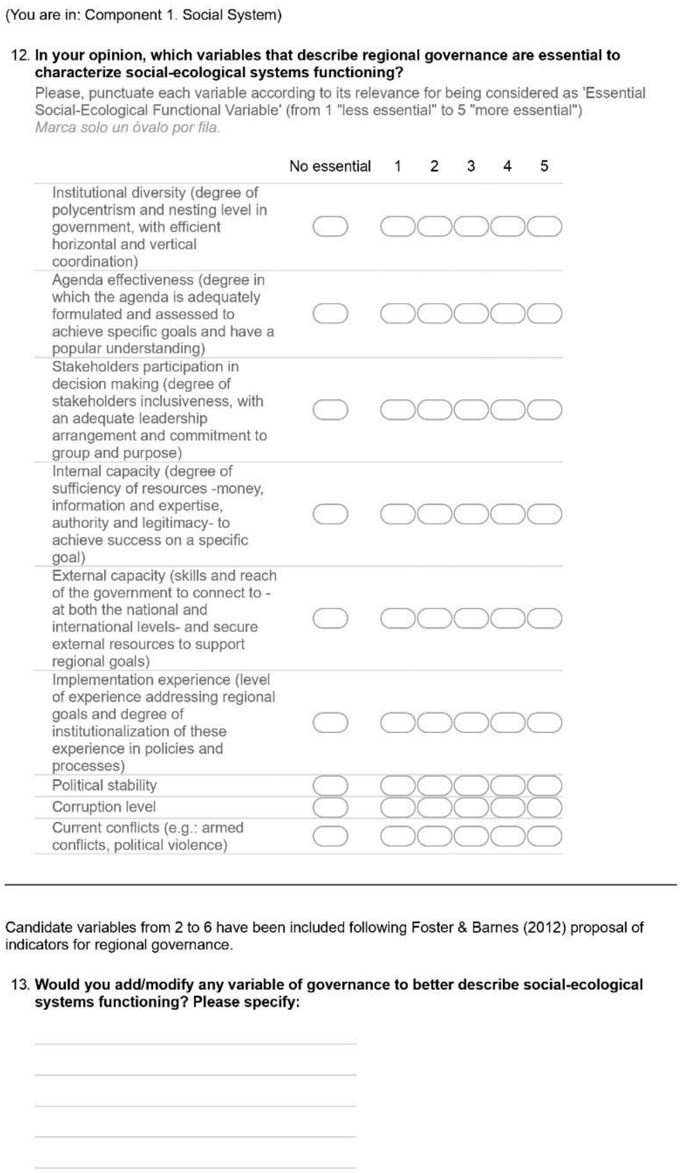
10. **In your opinion, which variables that describe human well-being and development are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Access to drinking water (e.g.: distance to drinking water)	○	○	○	○	○	○
Water sanitation (e.g.: % of houses using improved sanitation facilities)	○	○	○	○	○	○
Water scarcity	○	○	○	○	○	○
Electricity access	○	○	○	○	○	○
Access to internet	○	○	○	○	○	○
Educational level of the population (e.g.: illiteracy rate, % of population with higher education, school enrolment rate, out of school rate for adolescents)	○	○	○	○	○	○
Employment (e.g.: employment rate, unemployment rate)	○	○	○	○	○	○
Economic level of the population (e.g.: household income, income per capita)	○	○	○	○	○	○
Poverty (e.g. % of population with unsatisfied basic needs)	○	○	○	○	○	○
Social equality (e.g.: wealth distribution, women participation in government, women literacy rate, Gini Index)	○	○	○	○	○	○
Environmental quality (e.g.: air, water and soil pollution levels)	○	○	○	○	○	○
Access to healthcare and other basic social services (e.g.: % of population receiving public assistance)	○	○	○	○	○	○
Infant mortality rate	○	○	○	○	○	○
Life expectancy (e.g.: life expectancy at birth)	○	○	○	○	○	○
Total fertility rate	○	○	○	○	○	○
Average household size (e.g.: people per home)	○	○	○	○	○	○
Subjective well-being (e.g.: life satisfaction)	○	○	○	○	○	○
Security (e.g.: crime rate)	○	○	○	○	○	○
Social trust (in government, institutions)	○	○	○	○	○	○

11. **Would you add/modify any variable of social well-being and development to better describe social-ecological systems functioning? Please specify:**

Dimension 1c. Governance



(You are in: Component 1. Social System)

12. **In your opinion, which variables that describe regional governance are essential to characterize social-ecological systems functioning?**

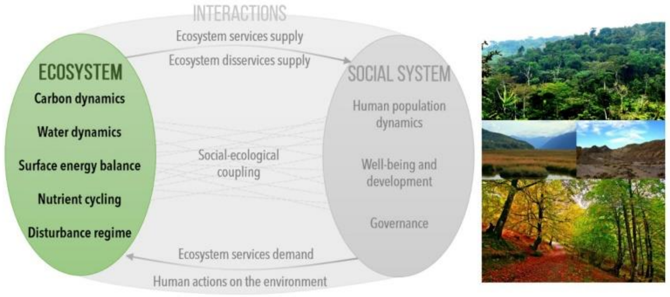
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Institutional diversity (degree of polycentrism and nesting level in government, with efficient horizontal and vertical coordination)	○	○	○	○	○	○
Agenda effectiveness (degree in which the agenda is adequately formulated and assessed to achieve specific goals and have a popular understanding)	○	○	○	○	○	○
Stakeholders participation in decision making (degree of stakeholders inclusiveness, with an adequate leadership arrangement and commitment to group and purpose)	○	○	○	○	○	○
Internal capacity (degree of sufficiency of resources -money, information and expertise, authority and legitimacy- to achieve success on a specific goal)	○	○	○	○	○	○
External capacity (skills and reach of the government to connect to - at both the national and international levels- and secure external resources to support regional goals)	○	○	○	○	○	○
Implementation experience (level of experience addressing regional goals and degree of institutionalization of these experience in policies and processes)	○	○	○	○	○	○
Political stability	○	○	○	○	○	○
Corruption level	○	○	○	○	○	○
Current conflicts (e.g.: armed conflicts, political violence)	○	○	○	○	○	○

Candidate variables from 2 to 6 have been included following Foster & Barnes (2012) proposal of indicators for regional governance.

13. **Would you add/modify any variable of governance to better describe social-ecological systems functioning? Please specify:**

COMPONENT 2. ECOSYSTEM



Dimension 2a. Carbon dynamics

(You are in: Component 2. Ecosystem)

14. **In your opinion, which variables that describe carbon dynamics are essential to characterize social-ecological systems functioning?**

Please, punctuate this variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Gross Primary Productivity (total amount of carbon fixed in the photosynthesis by plants in an ecosystem)	○	○	○	○	○	○
Net Primary Productivity (net productivity of organic carbon by plants in an ecosystem, e.g.: Net Ecosystem Exchange, Net Carbon Flux, carbon acumulation rate)	○	○	○	○	○	○
Respiration (natural carbon dioxide emissions by ecosystems)	○	○	○	○	○	○
Secondary productivity (represents the formation of living mass of a heterotrophic population or group of populations)	○	○	○	○	○	○
Organic Carbon Storage (biomass + litter + soil organic carbon)	○	○	○	○	○	○
Radiation Use Efficiency (organic carbon produced by unit of absorbed solar radiation)	○	○	○	○	○	○
Ecosystem composition by Plant Functional Types (plant classification according to their physical, phylogenetic and phenological characteristics)	○	○	○	○	○	○

15. **Would you add/modify any variable of carbon dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 2b. Water dynamics

(You are in: Component 2. Ecosystem)

16. **In your opinion, which variables that describe water dynamics are essential to characterize social-ecological systems functioning?**

Please, punctuate this variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Precipitation (water + snow)	○	○	○	○	○	○
Snow precipitations	○	○	○	○	○	○
Snow storage	○	○	○	○	○	○
Horizontal precipitation (e.g.: fog, dew, frost)	○	○	○	○	○	○
Extra-precipitation water contributions (e.g.: surface or groundwater inputs by rivers or acuifers, respectively)	○	○	○	○	○	○
Potential evapotranspiration	○	○	○	○	○	○
Actual evapotranspiration	○	○	○	○	○	○
Potencial water deficit -or excess- (due to climate conditions)	○	○	○	○	○	○
Actual water deficit -or excess- (due to climatic and ecohydrological conditions)	○	○	○	○	○	○
Evaporation - Transpiration ratio	○	○	○	○	○	○
Soil water infiltration capacity	○	○	○	○	○	○
Deep drainage (to aquifers)	○	○	○	○	○	○
Groundwater depth	○	○	○	○	○	○
Actual Soil Water Storage	○	○	○	○	○	○
Total water yield or "blue water" (runoff + deep drainage)	○	○	○	○	○	○
Flows of green water (water in and on soils and on vegetation canopy)	○	○	○	○	○	○
Precipitation Use Efficiency (organic carbon produced by unit of precipitation or by unit of evapotranspiration)	○	○	○	○	○	○
Vegetation water stress (e.g. precipitation minus [potential or actual] evapotranspiration)	○	○	○	○	○	○

17. **Would you add/modify any variable of water dynamics to better describe social-ecological systems functioning? Please specify:**

Dimension 2c. Surface energy balance

(You are in: Component 2. Ecosystem)

18. **In your opinion, which variables that describe surface energy balance are essential to characterize social-ecological systems functioning?**
    Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
    Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Net solar radiation (insolation)	○	○	○	○	○	○
Downward shortwave (visible [0.4-0.8 μm] + near ultraviolet [0.4-0.3 μm] + near infrared [0.8-2.5 μm]) radiation	○	○	○	○	○	○
Upward shortwave (visible [0.4-0.8 μm] + near ultraviolet [0.4-0.3 μm] + near infrared [0.8-2.5 μm]) radiation (i.e. albedo)	○	○	○	○	○	○
Upward longwave radiation (electromagnetic radiation)	○	○	○	○	○	○
Sensible heat, land surface temperature	○	○	○	○	○	○
Downward longwave radiation (thermal infrared [2.5-50 μm])	○	○	○	○	○	○
Latent heat flux (heat spent in water evapotranspiration)	○	○	○	○	○	○
Snow heat flux	○	○	○	○	○	○
Deep ground heat flux	○	○	○	○	○	○
Air temperature	○	○	○	○	○	○

19. **Would you add/modify any variable of surface energy balance to better describe social-ecological systems functioning? Please specify:**

Dimension 2d. Nutrient cycling

(You are in: Component 2. Ecosystem)

20. **In your opinion, which variables that describe nutrient cycling are essential to characterize social-ecological systems functioning?**
    Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
    Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Nitrogen fixation (atmospheric nitrogen fixed by N-fixer organisms, e.g.: Rhizobium)	○	○	○	○	○	○
Nitrogen deposition (wet and dry deposition of ammonium, nitrate, and particulate nitrogen)	○	○	○	○	○	○
Phosphorus deposition (e.g.: aerosols and atmospheric dust, etc.)	○	○	○	○	○	○
Gross nitrogen mineralization (e.g.: rate of production of ammonium in soils)	○	○	○	○	○	○
Net nitrogen mineralization (e.g.: net rate of production of plant-available nitrogen)	○	○	○	○	○	○
Soil phosphorus availability (e.g.: concentrations of non-occluded soil phosphorus)	○	○	○	○	○	○
Nitrogen status of plants (e.g.: plant tissue nitrogen concentrations)	○	○	○	○	○	○
Phosphorus status of plants (e.g.: plant tissue phosphorus concentrations)	○	○	○	○	○	○

21. **Would you add/modify any variable of nutrient cycling to better describe social-ecological systems functioning? Please specify:**

Dimension 2e. Disturbance regime

(You are in: Component 2. Ecosystem)

22. **In your opinion, which variables that describe disturance regime are essential to characterize social-ecological systems functioning?**

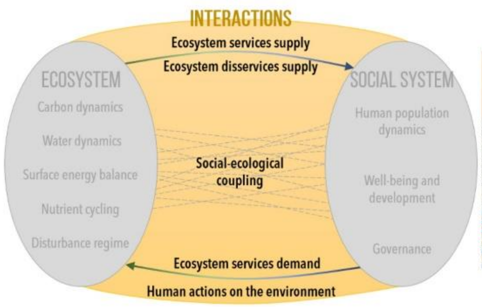
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Drought occurrence [frequency, severity, extension]	○	○	○	○	○	○
Fire occurrence [frequency, severity, extension]	○	○	○	○	○	○
Flood occurrence [frequency, severity, extension]	○	○	○	○	○	○
Herbivory (natural, not cattle grazing) [frequency, severity, extension]	○	○	○	○	○	○
Pest outbreaks occurrence [frequency, severity, extension]	○	○	○	○	○	○
Hurricanes/ storms occurence [frequency, severity, extension]	○	○	○	○	○	○
Landslides occurrence [frequency, severity, extension]	○	○	○	○	○	○
Volcanic eruptions occurrence [frequency, severity, extension]	○	○	○	○	○	○

23. **Would you add/modify any variable of disturbance regime to better describe social-ecological systems functioning? Please specify:**

COMPONENT 3. INTERACTIONS



Dimension 3a. Ecosystem services supply

(You are in: Component 3. Interactions)

24. **In your opinion, which variables that describe provisioning services supply are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Agricultural production	○	○	○	○	○	○
Livestock production	○	○	○	○	○	○
Surface and ground water sources for drinking	○	○	○	○	○	○
Surface and ground water sources for non-drinking purposes	○	○	○	○	○	○
Biomass-based energy sources	○	○	○	○	○	○
Fibres and other materials from plants, algae and animals for direct use or processing	○	○	○	○	○	○
Wild plants, algae and their outputs for food	○	○	○	○	○	○
Wild animals and their outputs for food	○	○	○	○	○	○

25. **In your opinion, which variables that describe regulation & maintenance services supply are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Hydrological cycle and water flow maintenance	○	○	○	○	○	○
Local climate regulation	○	○	○	○	○	○
Pollination and seed dispersal	○	○	○	○	○	○
Pest and disease control	○	○	○	○	○	○
Bioremediation	○	○	○	○	○	○
Chemical conditions maintenance of freshwaters and salt waters	○	○	○	○	○	○
Mass stabilisation and control of erosion rates	○	○	○	○	○	○
Ventilation (air renewal)	○	○	○	○	○	○

26. **In your opinion, which variables that describe cultural services supply are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Physical and experiential interactions (with plants, animals, landscapes, seascapes)	○	○	○	○	○	○
Intellectual and representative interacions (scientific, educational, heritage and cultural, entertainment, aesthetic contemplation)	○	○	○	○	○	○
Spiritual and/or emblematic (symbolic, sacred and/or religious) interactions	○	○	○	○	○	○

This candidate variables have been adapted from the Common International Classification of Ecosystem Services (CICES) 4.3 version ('class' level of this classification for provisioning and regulating services, and 'group' level for cultural services) (European Environment Agency, 2013).

27. **Would you add/modify any variable of ecosystem services supply to better describe social-ecological systems functioning? Please specify:**

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Dimension 3b. Ecosystem disservices supply

(You are in: Component 3. Interactions)

28. **In your opinion, which variables that describe ecosystem disservices supply are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Bio-economic (e.g.: biological invasions, agricultural and fisheries pests and diseases incidence, red tydes)	○	○	○	○	○	○
Abiotic-economic (e.g.: droughts and fires occurrence, siltation, leaching of nutrients)	○	○	○	○	○	○
Bio-health (e.g.: human diseases incidence from pathogens, allergens)	○	○	○	○	○	○
Abiotic-health (e.g.: flood and storm events occurrence)	○	○	○	○	○	○
Bio-cultural (e.g.: bird droppings on outdoor sculptures, tree roots cracking pavements)	○	○	○	○	○	○
Abiotic-cultural (e.g.: soil erosion rates, mud/landslide scar events, unpleasant odours from rotting organic matter)	○	○	○	○	○	○

It is noted that this candidate variables express the incidence of different kinds of harmful events. For simplicity, they have been classified according to their origin and primary dimension of human well-being affected, following Shackleton et al. (2016) approach.

29. **Would you add/modify any variable of ecosystem disservices supply to better describe social-ecological systems functioning? Please specify:**

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Dimension 3c. Ecosystem services demand

(You are in: Component 3. Interactions)

30. **In your opinion, which variables that describe the human capture of ecosystem goods and services are essential to characterize social-ecological systems functioning?**
Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")
Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Water use level (e.g.: water consumed per capita/ per year)	○	○	○	○	○	○
Water use for irrigated agriculture (e.g.: water use per hectare/ per year)	○	○	○	○	○	○
Energy use level (e.g.: energy consumed per capita/ per year)	○	○	○	○	○	○
Material use level (e.g.: raw materials consumed per capita/ per year)	○	○	○	○	○	○
Human Appropriation of Net Primary Production (e.g.: Tn C extracted/ per hectare/ per year)	○	○	○	○	○	○
Appropriation of land for agriculture	○	○	○	○	○	○
Nature tourism (e.g.: number of visitors to natural areas)	○	○	○	○	○	○

31. **Would you add/modify any variable of ecosystem services demand to better describe social-ecological systems functioning? Please specify:**

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Dimension 3d. Human actions on the environment

(You are in: Component 3. Interactions)

32. **In your opinion, which variables that describe the human actions on the environment are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Land cover/Land use change (e.g.: agriculturization, urbanisation, land abandonment)	○	○	○	○	○	○
Land use intensity	○	○	○	○	○	○
Territorial connectivity (e.g.: distance to main roads, travel time to major cities)	○	○	○	○	○	○
Anthropogenic water management (e.g.: water delivery, drainage and storage systems)	○	○	○	○	○	○
Anthropogenic carbon dioxide emissions (e.g.: per capita CO2 emissions, CO2 emissions by sector of economic activity)	○	○	○	○	○	○
Net carbon dioxide flux (e.g.: CO2 emissions - CO2 sequestration)	○	○	○	○	○	○
Pollution (toxic emissions and spills)	○	○	○	○	○	○
Eutrofization of water bodies	○	○	○	○	○	○
Soil erosion (by anthropogenic practices)	○	○	○	○	○	○
Conservation tillage (sustainable agricultural practices for soil preservation)	○	○	○	○	○	○
Ecological restoration	○	○	○	○	○	○
Land protection (e.g.: % of the territory declared as natural protected area with a management plan)	○	○	○	○	○	○

33. **Would you add/modify any variable of human actions on the environment to better describe social-ecological systems functioning? Please specify:**

Dimension 3e. Social-ecological coupling

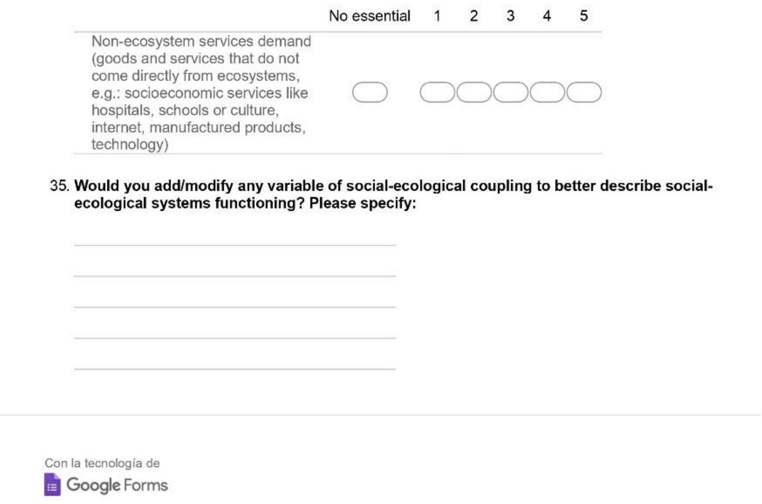
(You are in: Component 3. Interactions)

34. **In your opinion, which variables that describe the degree of connection of a community to its local environment are essential to characterize social-ecological systems functioning?**

Please, punctuate each variable according to its relevance for being considered as 'Essential Social-Ecological Functional Variable' (from 1 "less essential" to 5 "more essential")

Marca solo un óvalo por fila.

	No essential	1	2	3	4	5
Local natural capital dependence (e.g.: % of final ecosystem services consumed by the population that are provided directly by local environment)	○	○	○	○	○	○
Import [export] rates of agricultural and livestock products	○	○	○	○	○	○
Weight in the economy of the non-ecosystem services market (goods and services that do not come directly from ecosystems, e.g.: socioeconomic services like hospitals, schools or culture, internet, manufactured products, technology)	○	○	○	○	○	○
Airports [ports] activity	○	○	○	○	○	○
Dependence on fossil energies (e.g.: % of energy consumed coming from fossil resources)	○	○	○	○	○	○
Renewable energy use (e.g.: % of energy consumed coming from renewable sources)	○	○	○	○	○	○
Weight of sectors in the economy (agriculture vs. industry vs. services)	○	○	○	○	○	○
Weight of traditional (vs. intensive) agricultural and livestock sector in the economy	○	○	○	○	○	○
Population employed by sectors (agriculture vs. industry vs. services)	○	○	○	○	○	○
Population employed in traditional (vs. intensive) agriculture and stockbreeding	○	○	○	○	○	○
Biocapacity (capacity of ecosystems to meet people's local demand and assimilate waste products)	○	○	○	○	○	○
Land tenure (e.g.: % communal lands vs. private lands vs. government lands)	○	○	○	○	○	○
Access to natural or seminatural areas (e.g.: distance to a natural or seminatural area)	○	○	○	○	○	○
Human perception of ecosystem services (awareness level of the population about services provided by local ecosystems)	○	○	○	○	○	○
Human population ethnicity (e.g.: % of indigenous population)	○	○	○	○	○	○
Cultural attachment to nature	○	○	○	○	○	○
Local green initiatives (e.g.: in agriculture, cities, touristic activities, local companies)	○	○	○	○	○	○



	No essential	1	2	3	4	5
Non-ecosystem services demand (goods and services that do not come directly from ecosystems, e.g.: socioeconomic services like hospitals, schools or culture, internet, manufactured products, technology)	○	○	○	○	○	○

35. **Would you add/modify any variable of social-ecological coupling to better describe social-ecological systems functioning? Please specify:**

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Appendix 1E. Tables

Table E1. Preliminary and enhanced lists of variables for characterizing and monitoring SESs, structured into dimensions across the three components of a SES. The preliminary list contains 77 variables structured into 12 dimensions and was generated through literature review and an initial expert workshop. The improved list contains 149 variables structured into 13 dimensions and was the result of analyzing the preliminary survey results (56 responses) in a second scientific workshop. This improved list was then introduced in the final survey with the aim of using scientist scorings to prioritize the variables.

Component	Dimension	Preliminary list (77 variables in 12 dimensions)	Improved list (149 variables in 13 dimensions)
Social system	Human population dynamics	Population density	Population density
		Population distribution	Population distribution
		Population size	Population size
		Human migrations	Human migrations
		Age structure	Age structure
		Sex Ratio	Sex Ratio
			Population growth rate by natural increase
			Population growth rate by immigration
	Wellbeing and development	Access to drinking water	Access to drinking water
		Water sanitation	Water sanitation
		Electricity access	Electricity access
		Access to internet	Access to internet
		Educational level of the population	Educational level of the population
		Employment	Employment
		Economic level of the population	Economic level of the population
		Social equity	Social equity
		Environmental quality	Environmental quality
		Mortality	Infant mortality rate
		Overcrowding	Average household size
		Life expectancy	Life expectancy
		Institutional diversity	-
		Land protection	-
			Water scarcity
			Poverty

			Access to healthcare and other basic social services
			Total fertility rate
			Subjective wellbeing
			Security
			Social trust
	Governance (not included in 1st survey)		Institutional diversity
			Agenda effectiveness[1]
			Stakeholders participation in decision making[1]
			Internal capacity[1]
			External capacity[1]
			Implementation experience[1]
			Political stability
			Corruption level
			Current conflicts
Ecological system	Organic carbon dynamics (Carbon dynamics in 1st survey)	Net Primary Productivity	Net Primary Productivity
			Gross Primary Productivity
			Respiration
			Secondary productivity
			Organic carbon storage
			Radiation Use Efficiency
			Ecosystem composition by Plant Functional Types
	Water dynamics	Evapotranspiration	Actual evapotranspiration
			Potential evapotranspiration
			Precipitation
			Snow precipitations
			Snow storage
			Horizontal precipitation
			Extra-precipitation water contributions
			Potential water deficit -or excess-
			Actual water deficit -or excess-
			Evaporation - Transpiration ratio

		Soil water infiltration capacity
		Deep drainage
		Groundwater depth
		Actual Soil Water Storage
		Total water yield or "blue water"
		Flows of green water
		Precipitation Use Efficiency
		Vegetation water stress
Surface energy balance (Energy dynamics in 1st survey)	Land surface energy balance	-
	Albedo	Upward shortwave radiation
	Land surface temperature	Sensible heat, land surface temperature
		Net solar radiation
		Downward shortwave radiation
		Upward longwave radiation
		Downward longwave radiation
		Latent heat flux
		Snow heat flux
		Deep ground heat flux
		Air temperature
Nutrient cycling	Nitrogen cycling	-
	Phosphorus cycling	-
		Nitrogen fixation
		Nitrogen deposition
		Phosphorus deposition
		Gross nitrogen mineralization
		Net nitrogen mineralization
		Soil phosphorus availability
		Nitrogen status of plants
		Phosphorus status of plants
Disturbance regime	Drought occurrence	Drought occurrence
	Fire occurrence	Fire occurrence
		Flood occurrence
		Herbivory

			Pest outbreaks occurrence
			Hurricanes/storms occurrence
			Landslides occurrence
			Volcanic eruptions occurrence
Interactions	Ecosystem service supply[2]†	Cropland production (P)	Cropland production (P)
		Livestock production (P)	Livestock production (P)
		Surface and groundwater sources for drinking (P)	Surface and groundwater sources for drinking (P)
		Surface and ground water sources for nondrinking purposes (P)	Surface and ground water sources for nondrinking purposes (P)
		Biomass-based energy sources (P)	Biomass-based energy sources (P)
		Fibres and other materials from plants, algae and animals for direct use or processing (P)	Fibres and other materials from plants, algae and animals for direct use or processing (P)
		Wild plants, algae and their outputs for food (P)	Wild plants, algae and their outputs for food (P)
		Wild animals and their outputs for food (P)	Wild animals and their outputs for food (P)
		Hydrological cycle and water flow maintenance (R)	Hydrological cycle and water flow maintenance (R)
		Global climate regulation (R)	Local climate regulation (R)
		Pollination and seed dispersal (R)	Pollination and seed dispersal (R)
		Pest and disease control (R)	Pest and disease control (R)
		Bioremediation (R)	Bioremediation (R)
		Chemical conditions maintenance of freshwaters and salt waters (R)	Chemical conditions maintenance of freshwaters and salt waters (R)
		Mass stabilisation and control of erosion rates (R)	Mass stabilisation and control of erosion rates (R)
		Ventilation and transpiration (R)	Ventilation (R)
		Weathering, decomposition and fixing rates (for soil formation) (R)	-
		Physical and experiential interactions (C)	Physical and experiential interactions (C)
		Intellectual and representative interacions (C)	Intellectual and representative interacions (C)

	Spiritual and/or emblematic interactions (C)	Spiritual and/or emblematic interactions (C)
Ecosystem disservice supply[3]	Bio-economic	Bio-economic
	Abiotic-economic	Abiotic-economic
	Bio-health	Bio-health
	Abiotic-health	Abiotic-health
	Bio-cultural	Bio-cultural
	Abiotic-cultural	Abiotic-cultural
Ecosystem service demand	Water use level	Water use level
	Energy use level	Energy use level
	Material use level	Material use level
	Human Appropriation of Net Primary Production	Human Appropriation of Net Primary Production
		Water use for irrigated crops
		Appropriation of land for agriculture
		Nature tourism
Human actions on the environment	Land use intensity	Land use intensity
	Isolation	Territorial connectivity
	Carbon dioxide emissions	Anthropogenic carbon dioxide emissions
	Pollution	Pollution
		Land cover/Land use change
		Anthropogenic water management
		Net carbon dioxide flux
		Eutrophication of water bodies
		Soil erosion
		Conservation tillage
		Ecological restoration
		Land protection
Social-ecological coupling	Local natural capital dependence	Local natural capital dependence
	Import [export] rates	Import [export] rates of crop and livestock products
	Weight in the economy of the non-ecosystem services market	Weight in the economy of the non-ecosystem services market
	Airports [ports] activity	Airports [ports] activity

	Dependence on fossil energies	Dependence on fossil energies
	Renewable energy use	Renewable energy use
	Weight of farming [industry, services] sector in the economy	Weight of sectors in the economy
	Population employed in farming [industry, services] sectors	Population employed by sectors
	Land tenure structure	Land tenure
	Access to natural or semi natural areas	Access to natural or seminatural areas
	Human perception of ecosystem services	Human perception of ecosystem services
	Human population ethnicity	Human population ethnicity
	Local green initiatives	Local green initiatives
	Non-ecosystem services demand	Non-ecosystem services demand
		Weight of traditional (vs. intensive) agricultural sector in the economy
		Population employed in traditional (vs. intensive) agriculture
		Biocapacity
		Cultural attachment to nature

† P = provisioning services; R = regulating services; C = cultural services

[1] Foster, K. A., and W. R. Barnes. 2012. Reframing Regional Governance for Research and Practice. *Urban Affairs Review* 48(2):272–283.

[2] Haines-Young, R., and M. Potschin. 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012. [online] URL: https://www.cices.eu

[3] Shackleton, C. M., S. Ruwanza, G. K. Sinasson Sanni, S. Bennett, P. De Lacy, R. Modipa, N. Mtati, M. Sachikonye, and G. Thondhlana. 2016. Unpacking Pandora's Box: Understanding and Categorising Ecosystem Disservices for Environmental Management and Human Wellbeing. *Ecosystems* 19(4):587–600. [online] URL: https://doi.org/10.1007/s10021-015-9952-z

Table E2. List of prioritized variables for characterizing and monitoring SES (extended version with examples and explanations). The list is structured into 13 dimensions across the three components of a SES (Fig. 2 in the paper). Priority level 1 (top priority) includes variables with relevance and consensus above the 90th percentile; level 2 includes variables between the 75th and 90th percentiles; level 3 includes variables with relevance above the 75th percentile but consensus between the 50th and 75th percentiles and vice versa; and finally, level 4 includes variables with relevance and consensus between the 50th and 75th percentiles. The nonpriority category includes variables with relevance and consensus below the 50th percentile.

Component	Dimension	Priority variables (decreasing priority from 1 to 4)				Nonpriority variables
		Level 1	Level 2	Level 3	Level 4	
Social system	Human population dynamics			Population density Population distribution (e.g., % rural population vs. % urban population)		Age structure (e.g., median age, population ageing index, dependency ratio) Human migrations (e.g., ratio of immigration/emigration) Population growth rate by immigration Population growth rate by natural increase Population size Sex Ratio
	Wellbeing and development		Access to drinking water (e.g., distance to drinking water)	Water sanitation (e.g., % of houses using improved sanitation facilities) Water scarcity		Access to healthcare and other basic social services (e.g., % of population receiving public assistance) Access to internet

	Educational level (e.g., illiteracy rate, % of population with higher education, school enrolment rate, out of school rate for adolescents) Environmental quality (e.g., air, water and soil pollution levels) Poverty (e.g., % of population with unsatisfied basic needs) Social equity (e.g., wealth distribution, women participation in government, women literacy rate, Gini Index)			Average household size (e.g., people per home) Economic level (e.g., household income, income per capita) Electricity access Employment (e.g., employment rate, unemployment rate) Infant mortality rate Life expectancy (e.g., life expectancy at birth) Security (e.g., crime rate) Social trust (in government, institutions) Subjective wellbeing (e.g., life satisfaction) Total fertility rate
Governance	Current conflicts (e.g., armed conflicts, political violence)	Corruption level Political stability		Agenda effectiveness (degree in which the agenda is adequately formulated and assessed to achieve specific goals and have a popular understanding)[1] External capacity (skills and reach of the government to connect to - at

both the national and international levels- and secure external resources to support regional goals)[1]

Implementation experience (level of experience addressing regional goals and degree of institutionalization of these experience in policies and processes)[1]

Institutional diversity (degree of polycentrism and nesting level in government, with efficient horizontal and vertical coordination)

Internal capacity (degree of sufficiency of resources -money, information and expertise, authority and legitimacy- to achieve success on a specific goal)

Stakeholders participation in decision making (degree of stakeholder’s inclusiveness, with an adequate leadership arrangement and commitment to group and purpose)

Ecological system	Organic carbon dynamics			Net primary productivity (net productivity of organic carbon by plants in an ecosystem, e.g., Net Ecosystem Exchange, Net Carbon Flux, carbon accumulation rate) Organic carbon storage (biomass + litter + soil organic carbon)	Ecosystem composition by plant functional type (plant classification according to their physical, phylogenetic and phenological characteristics)	Gross Primary Productivity (total amount of carbon fixed in the photosynthesis by plants in an ecosystem) Radiation Use Efficiency (organic carbon produced by unit of absorbed solar radiation) Respiration (natural carbon dioxide emissions by ecosystems) Secondary productivity (represents the formation of living mass of a heterotrophic population or group of populations)
	Water dynamics		Precipitation (water + snow)	Actual evapotranspiration Actual water deficit -or excess- (due to climatic and ecohydrological conditions)	Soil water infiltration capacity	Actual Soil Water Storage Deep drainage (to aquifers) Extra-precipitation water contributions (e.g., surface or groundwater inputs by rivers or aquifers, respectively) Evaporation - Transpiration ratio Flows of green water (water in and on soils and on vegetation canopy) Groundwater depth Horizontal precipitation (e.g., fog, dew, frost) Potential evapotranspiration

			Potential water deficit -or excess- (due to climate conditions)
			Precipitation Use Efficiency (organic carbon produced by unit of precipitation or by unit of evapotranspiration)
			Snow precipitations
			Snow storage
			Total water yield or "blue water" (runoff + deep drainage)
			Vegetation water stress (e.g., precipitation minus [potential or actual] evapotranspiration)
Surface energy balance	Net solar radiation (insolation)	Land surface temperature (sensitive heat)	Air temperature
			Deep ground heat flux
			Downward longwave radiation (thermal infrared [2.5-50 μm])
			Downward shortwave radiation (visible [0.4-0.8 μm] + near ultraviolet [0.4-0.3 μm] + near infrared [0.8-2.5 μm])
			Latent heat flux (heat spent in water evapotranspiration)
			Snow heat flux
			Upward longwave radiation (electromagnetic radiation)

					Upward shortwave radiation (visible [0.4-0.8 μm] + near ultraviolet [0.4-0.3 μm] + near infrared [0.8-2.5 μm]) (i.e. albedo)
Nutrient cycling	Nitrogen fixation (atmospheric nitrogen fixed by N-fixer organisms, e.g., Rhizobium)		Soil phosphorus availability (e.g., concentrations of non-occluded soil phosphorus)	Nitrogen deposition (wet and dry deposition of ammonium, nitrate and particulate nitrogen)	Gross nitrogen mineralization (e.g., rate of production of ammonium in soils) Net nitrogen mineralization (e.g., net rate of production of plant-available nitrogen) Nitrogen status of plants (e.g., plant tissue nitrogen concentrations) Phosphorus deposition (e.g., aerosols and atmospheric dust, etc.) Phosphorus status of plants (e.g., plant tissue phosphorus concentrations)

	Disturbance regime	Drought occurrence Flood occurrence	Fire occurrence	Hurricanes/storms occurrence Pest outbreaks occurrence		Herbivory (natural, not cattle grazing) Landslides occurrence Volcanic eruptions occurrence
Interactions	Ecosystem service supply[2]†	Cropland production (P) Livestock production (P) Surface and groundwater sources for drinking (P) Hydrological cycle and water flow maintenance (R)		Surface and groundwater sources for nondrinking purposes (P) Local climate regulation (R) Pest and disease control (R) Pollination and seed dispersal (R)	Chemical conditions maintenance of freshwater and saltwater (R)	Biomass-based energy sources (P) Bioremediation (R) Fibres and other materials from plants, algae and animals for direct use or processing (P) Intellectual and representative interactions (scientific, educational, heritage and cultural, entertainment, aesthetic contemplation) (C) Mass stabilisation and control of erosion rates (R) Physical and experiential interactions (with plants, animals, landscapes, seascapes) (C) Spiritual and/or emblematic interactions (symbolic, sacred and/or religious) (C) Ventilation (air renewal) (R) Wild plants, algae and their outputs for food (P) Wild animals and their outputs for food (P)

Ecosystem disservice supply[3]				Abiotic-economic (e.g., droughts and fires occurrence, siltation, leaching of nutrients) Bio-economic (e.g., biological invasions, agricultural and fisheries pests and diseases incidence, red tides)	Abiotic-cultural (e.g., soil erosion rates, mud/landslide scar events, unpleasant odours from rotting organic matter) Abiotic-health (e.g., flood and storm events occurrence) Bio-cultural (e.g., bird droppings on outdoor sculptures, tree roots cracking pavements) Bio-health (e.g., human diseases incidence from pathogens, allergens)
Ecosystem service demand		Appropriation of land for agriculture Energy use level (e.g., energy consumed per capita and year) Water use level (e.g., water consumed per capita and year) Water use for irrigated crops (e.g., water use per hectare and year)	Material use level (e.g., raw materials consumed per capita and year)	Human Appropriation of Net Primary Production (HANPP) (e.g., Tn C extracted per hectare and year)	Nature tourism (e.g., number of visitors to natural areas)

Human actions on the environment	Land cover/Land use change (e.g., agriculturization, urbanisation, land abandonment) Land use intensity	Eutrophication of water bodies Land protection (e.g., % of the territory declared as natural protected area with a management plan) Pollution (toxic emissions and spills) Soil erosion (by anthropogenic practices)	Anthropogenic water management (e.g., water delivery, drainage and storage systems)	Net CO_2 flux (e.g., CO2 emissions - CO2 sequestration) Territorial connectivity (e.g., distance to main roads, travel time to major cities)	Anthropogenic carbon dioxide emissions (e.g., per capita CO2 emissions, CO2 emissions by sector of economic activity) Conservation tillage (sustainable agricultural practices for soil preservation) Ecological restoration
Social-ecological coupling	Local natural capital dependence (e.g., % of final ecosystem services consumed by the population that are provided directly by local environment)		Access to natural and semi-natural areas (e.g., distance to a natural or seminatural area) Biocapacity (capacity of ecosystems to meet people's local demand and assimilate waste products)	Import [export] rates of agricultural products Renewable energy use (e.g., % of energy consumed coming from renewable sources)	Airports [ports] activity Cultural attachment to nature Dependence on fossil energies (e.g., % of energy consumed coming from fossil resources) Human perception of ecosystem services (awareness level of the population about services provided by local ecosystems) Human population ethnicity (e.g., % of indigenous population)

Land tenure (e.g., % communal lands vs. private lands vs. government lands)

Local green initiatives (e.g., in agriculture, cities, touristic activities, local companies)

Non-ecosystem services demand (goods and services that do not come directly from ecosystems, e.g., socioeconomic services like hospitals, schools or culture, internet, manufactured products, technology)

Population employed by sectors (agriculture vs. industry vs. services)

Population employed in traditional (vs. intensive) agriculture

Weight in the economy of the non-ecosystem services market (goods and services that do not come directly from ecosystems, e.g., socioeconomic services like hospitals, schools or culture, internet, manufactured products, technology)

Weight of sectors in the economy (agriculture vs. industry vs. services)
Weight of traditional (vs. intensive) agricultural sector in the economy

† P = provisioning services; R = regulating services; C = cultural services.

[1] Foster, K. A., and W. R. Barnes. 2012. Reframing Regional Governance for Research and Practice. *Urban Affairs Review* 48(2):272–283. [online] URL: https://doi.org/10.1177/1078087411428121

[2] Haines-Young, R., and M. Potschin. 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012. [online] URL: https://www.cices.eu

[3] Shackleton, C. M., S. Ruwanza, G. K. Sinasson Sanni, S. Bennett, P. De Lacy, R. Modipa, N. Mtati, M. Sachikonye, and G. Thondhlana. 2016. Unpacking Pandora’s Box: Understanding and Categorising Ecosystem Disservices for Environmental Management and Human Wellbeing. *Ecosystems* 19(4):587–600. [online] URL: https://doi.org/10.1007/s10021-015-9952-z

In this paper, ecosystem disservices are defined as *“the ecosystem generated functions, processes and attributes that result in perceived or actual negative impacts on human wellbeing.”*

We based on Shackleton et al. (2016) classification to distinguish among 6 categories of ecosystem disservices, according to their origin (biological or abiotic) and the nature of their impacts on human wellbeing (economic; physical and mental health and safety; aesthetics and culture): bio-economic, abiotic-economic, bio-health, abiotic-health, bio-cultural, abiotic-cultural. Examples of ecosystem disservices for each category are include in the Table above.

Table E3. Examples of studies that have used prioritized variables to map SES distribution and dynamics. The specific metrics used to map SESs associated with the priority variables identified in our study are listed. Nonpriority variables (those that obtained the lowest scores in the survey) and additional variables not included in our list are also matched to the metrics used to map SESs.

Component	Variable	Variable priority level	Reference	Metric
Social system	Educational level	2	Castellarini et al. (2014)	Human Development Index
			Hamann et al. (2016)	People with completed secondary schooling or higher
			Martín-López et al. (2017)	Illiterates
				People with university degree
			Rocha et al. (2020)	Literacy rate
			Vallejos et al. (2020)	School density
	Poverty	2	Václavík et al. (2013)	Gross Domestic Product
			Castellarini et al. (2014)	Human Development Index
			Hamann et al. (2016)	Household income
			Vallejos et al. (2020)	Unsatisfied basic needs
	Environmental quality	2	Queiroz et al. (2015)	Standing water quality
				Running water quality
			Dittrich et al. (2017)	Soil quality
	Conflicts	2	Dressel et al. (2018)	Potential for conflict index on moose managers evaluation of moose population
	Population density	3	Ellis and Ramankutty (2008) Asselen and Verburg (2012) Václavík et al. (2013) Hamann et al. (2015) Renard et al. (2015) Dittrich et al. (2017)	Population density

		Martín-López et al. (2017) Spake et al. (2017) Levers et al. (2018) Vallejos et al. (2020)	
		Rocha et al. (2020)	Population density Change in population density
Population distribution	3	Ellis and Ramankutty (2008)	Urban and non-urban population
Political stability	3	Václavík et al. (2013)	Political stability index
Population size	nonpriority	Hanspach et al. (2016)	Total population size
Migrations	nonpriority	Hanspach et al. (2016)	Net migration
		Martín-López et al. (2017)	Foreign population
		Rocha et al. (2020)	Inter & intra regional migrations
Age structure	nonpriority	Hanspach et al. (2016)	Proportion of pupils
		Martín-López et al. (2017)	People younger than 20 People older than 65
		Rocha et al. (2020)	Ratio of children
Sex ratio	nonpriority	Dittrich et al. (2017)	Ratio female/male
		Rocha et al. (2020)	Ratio of woman
Life expectancy	nonpriority	Hamann et al. (2016)	Average age of death
Employment	nonpriority	Hamann et al. (2016)	Unemployed people Discouraged work-seeker
		Hanspach et al. (2016)	Unemployment rate

			Dittrich et al. (2017)	Unemployment rate
			Martín-López et al. (2017)	Unemployed inhabitants
			Levers et al. (2018)	Total labour input
			Vallejos et al. (2020)	Permanent workers
	Economic level	nonpriority	Václavík et al. (2013)	Gross Domestic Product
			Castellarini et al. (2014)	Human Development Index
			Hamann et al. (2015)	Household income
			Hamann et al. (2016)	Household income
			Martín-López et al. (2017)	Income per capita
			Levers et al. (2018)	Economic activity index
	Access to internet	nonpriority	Martín-López et al. (2017)	Number of ADSL lines
	Security	nonpriority	Hamann et al. (2016)	Property ownership (Percentage of households where dwelling is owned and fully paid off)
	Internal capacity of the government	nonpriority	Dittrich et al. (2017)	District debts
	Stakeholders participation in decision making	nonpriority	Dressel et al. (2018)	Proportion of general public that are relevant actors
Ecological system	Precipitation	2	Asselen and Verburg (2012)	Precipitation
			Václavík et al. (2013)	Precipitation Precipitation seasonality
			Dittrich et al. (2017)	Mean precipitation vegetation period
			Martín-López et al. (2017)	Mean annual precipitation Minimum annual precipitation Maximum annual precipitation
			Spake et al. (2017)	Annual precipitation

		Rocha et al. (2020)	Number of months with precipitation >60 mm
Net Primary Productivity	3	Alessa et al. (2008)	Net Primary Productivity Index
		Ellis and Ramankutty (2008)	Net Primary Productivity (g m^{-2})
		Václavík et al. (2013)	NDVI – mean NDVI – seasonality
		Hamann et al. (2015)	Area with high grazing potential
		Spake et al. (2017)	Potential Net Primary Productivity (tC m^{-2} yr)
		Vallejos et al. (2020)	EVI – mean EVI – seasonality
Organic carbon storage	3	Raudsepp-Hearne et al. (2010)	Carbon sequestration (kg C km^{-2})
		Asselen and Verburg (2012)	Soil organic carbon (g C kg^{-1} of soil)
		Václavík et al. (2013)	Soil organic carbon (g C kg^{-1} of soil)
		Renard et al. (2015)	Carbon sequestration (kg C km^{-2})
		Spake et al. (2017)	Carbon stocks from above-ground and below-ground biomass, dead organic matter and soils (tC km^{-2})
		Levers et al. (2018)	Soil organic carbon (tC ha^{-1})
Actual evapotranspiration	3	Martín-López et al. (2017)	Mean annual evapotranspiration Minimum annual evapotranspiration Maximum annual evapotranspiration
Actual water deficit (or excess)	3	Levers et al. (2018)	Ratio of mean annual precipitation & mean annual potential evapotranspiration
		Rocha et al. (2020)	Mean aridity gradient
Net solar radiation	3	Václavík et al. (2013)	Solar radiation (W m^{-2})
		Dittrich et al. (2017)	Mean sunshine duration

Soil phosphorus availability	3	Raudsepp-Hearne et al. (2010) Queiroz et al. (2015)	Soil phosphorus retention
Land surface temperature	4	Asselen and Verburg (2012)	Mean temperature
		Václavík et al. (2013)	Temperature
			Diurnal temperature range
			Extreme temperatures
		Dittrich et al. (2017)	Mean temperature vegetation period
		Levers et al. (2018)	Growing degree days (T>0º)
		Rocha et al. (2020)	Mean temperature
Groundwater depth	nonpriority	Dittrich et al. (2017)	Groundwater level
Biodiversity	not in our list	Václavík et al. (2013)	Species richness
		Castellarini et al. (2014)	Distribution of ecoregions
		Hanspach et al. (2016)	Species richness
		Spake et al. (2017)	Species richness
		Levers et al. (2018)	Distribution of ecoregions
Natural capital	not in our list	Vallejos et al. (2020)	Native forest area
Other abiotic conditions	not in our list	Asselen and Verburg (2012)	Soil characteristics
			Altitude
			Slope
		Castellarini et al. (2014)	Ecorregions map
		Renard et al. (2015)	Soil capability for agriculture
		Hanspach et al. (2016)	Altitude
			Terrain ruggedness
			Slope
			Terrain wetness index
			Heatload

			Sinare et al. (2016)	Topography
			Dittrich et al. (2017)	Ruggedness
			Martín-López et al. (2017)	Altitude Slope Lithology Geomorphology
			Spake et al. (2017)	Elevation
			Levers et al. (2018)	Topographic heterogeneity
			Rocha et al. (2020)	Slope
Interactions	Cropland production	1	Raudsepp-Hearne et al. (2010) Václavík et al. (2013) Hamann et al. (2015) Queiroz et al. (2015) Renard et al. (2015) Dittrich et al. (2017) Spake et al. (2017) Levers et al. (2018)	Cropland production
			Rocha et al. (2020)	Variance of crop production Kilocalories for diverse crops
			Vallejos et al. (2020)	Annual crops area
	Livestock production	1	Raudsepp-Hearne et al. (2010) Asselen and Verburg (2012) Hamann et al. (2015) Queiroz et al. (2015) Renard et al. (2015) Dittrich et al. (2017) Martín-López et al. (2017) Levers et al. (2018)	Livestock production
			Rocha et al. (2020)	Cattle per km^2 Small ruminants per capita

		Vallejos et al. (2020)	Forage crops area Pregnant cows
Surface and groundwater sources for drinking	1	Raudsepp-Hearne et al. (2010)	Drinking water quality - IQBP indicator (1-5)
		Dittrich et al. (2017)	Clean water - nitrogen concentration in rivers (mg N l^{-1})
Hydrological cycle and water flow maintenance	1	Hamann et al. (2015)	Mean annual runoff
		Renard et al. (2015)	Flood control
		Dittrich et al. (2017)	Flood protection (biophysical dependent flood regulation by catchments)
		Spake et al. (2017)	Physical water quantity regulation
		Rocha et al. (2020)	Soil water holding capacity
Land cover/Land use change	1	Ellis and Ramankutty (2008)* Asselen and Verburg (2012)* Václavík et al. (2013) Castellarini et al. (2014)* Hamann et al. (2015)* Hanspach et al. (2016)* Sinare et al. (2016)* Martín-López et al. (2017) * Spake et al. (2017)* Levers et al. (2018) Vallejos et al. (2020)*	Multiple categories * (These studies include land cover and land use variables but not address changes directly)
		Dressel et al. (2018)	Diversity of land cover type
Land use intensity	1	Asselen and Verburg (2012)	Efficiency of agricultural production
		Václavík et al. (2013)	Multidimensional (N fertilizer, irrigation, soil erosion, yields, HANPP)

		Hanspach et al. (2016)	Landscape heterogeneity
		Martín-López et al. (2017)	Cropland irrigation
			Greenhouses crops
		Levers et al. (2018)	Wood production
			Fertilizer application rates
			Yields
			Stocking density
			Grassland yields
		Vallejos et al. (2020)	Irrigated area
			Tractor density
			Stocking density
Soil erosion	1	Václavík et al. (2013)	Soil erosion
Land protection	1	Martín-López et al. (2017)	Surface in the municipality in the protected area
		Spake et al. (2017)	Protected area coverage (Natura 2000)
		Levers et al. (2018)	Changes in protected areas (Natura 2000)
Local natural capital dependence	1	Hamann et al. (2015)	Demand of ecosystem services provided by the local environment (wood for heating, wood production, crop production, animal production, freshwater, building materials)
			Female headed households
Water use level	2	Hamann et al. (2015)	Use of freshwater from a natural source (a river or spring)
		Martín-López et al. (2017)	Water consumption
		Rocha et al. (2020)	Dams
Water use for irrigated crops	2	Václavík et al. (2013)	Irrigated surface

Appropriation of land for agriculture	2	Ellis and Ramankutty (2008) Raudsepp-Hearne et al. (2010) Asselen and Verburg (2012) Václavík et al. (2013) Hamann et al. (2015) Renard et al. (2015) Queiroz et al. (2015) Hanspach et al. (2016) Spake et al. (2017) Martín-López et al. (2017) Levers et al. (2018)	Surface dedicated to agriculture
Pollination and seed dispersal	3	Queiroz et al. (2015)	Amount of pollinator habitat within a buffer of 200m from crop production areas
		Dittrich et al. (2017)	Pollination potential (habitat suitable for pollinators)
Bio-economic ecosystem disservices	4	Dressel et al. (2018)	Competition (presence of other ungulate species) Predation (presence of bears) Predation (presence of wolves) Fresh browsing damage on Scots pine (Pinus sylvestris)
Human Appropriation of Net Primary Production (HANPP)	4	Václavík et al. (2013)	HANPP
		Levers et al. (2018)	HANPP harvest for arable croplands, permanent crops and grasslands
Territorial connectivity	4	Václavík et al. (2013)	Accessibility (travel time to major cities and market places)
		Hamann et al. (2015)	Distance to city
		Renard et al. (2015)	Distance from main city

		Hanspach et al. (2016)	Remoteness (travel time by car to the next town >20000)
		Levers et al. (2018)	Accessibility (travel time to major city >50000)
		Rocha et al. (2020)	Market access index
		Vallejos et al. (2020)	Transport network connectivity (road density)
Import and export rates of agricultural products	4	Asselen and Verburg (2012)	Market influence Market accessibility
Wild plants, algae and their outputs for food	nonpriority	Raudsepp-Hearne et al. (2010)	Maple syrup
Fibres and other materials from plants, algae and animals for direct use or processing	nonpriority	Dressel et al. (2018)	Index of moose forage availability Variation in moose forage availability over 10 years
		Levers et al. (2018)	Grassland yields Wood production
Wild animals and their outputs for food (P)	nonpriority	Dressel et al. (2018)	Size of moose management area Number of shot moose per square kilometre Ratio of moose to other ungulate species Frequency of moose meat consumption
Biomass-based energy sources	nonpriority	Hamann et al. (2015)	Wood for cooking, wood for heating
		Dittrich et al. (2017)	Energy crops (amount of methane provided by crops for biogas production)
		Spake et al. (2017)	Potential woody biomass supply for stemwood and logging residues
Bioremediation	nonpriority	Dittrich et al. (2017)	Ability of rivers to remove nitrogen

Bio-health ecosystem disservices	nonpriority	Dressel et al. (2018)	Number of moose-car-collisions
Human perceptions of ecosystem services	nonpriority	Sinare et al. (2016)	Use of ecosystem services reported by locals
Nitrogen fertilizer	not in our list	Václavík et al. (2013)	Fertilized surface
		Levers et al. (2018)	Fertilizer application rates [kg ha^{-1}]; <50 kg ha^{-1}, 50-150 kg ha^{-1}, >150 kg ha^{-1}
Urban solid waste	not in our list	Martín-López et al. (2017)	Urban solid waste production (Ton $year^{-1}$ ha^{-1})
Weight of sectors in the economy	nonpriority	Václavík et al. (2013)	GDP in agriculture Capital stock in agriculture
		Martín-López et al. (2017)	Hotel bedroom places
		Levers et al. (2018)	Economic size of farms Total monetary inputs in farms
		Rocha et al. (2020)	Ratio of farmers
Land tenure	nonpriority	Hamann et al. (2015)	Area under traditional authority rule
		Dressel et al. (2018)	Level of self-organization (geographic coverage of moose management units) Number of sub-units (i.e. license areas) per moose management area Diversity index of forest ownership types Diversity index of agriculture ownership types Property size classes of private forest owners
		Levers et al. (2018)	Total utilised agricultural area (owner occupation or rented for >= 1 year)
		Vallejos et al. (2020)	Area with legal type of farmer ‘Physical Person’ Area with land tenure regime ‘Owner’

Ethnicity	nonpriority	Hanspach et al. (2016)	Proportion of the main ethnic groups

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Appendix 1F. Figures

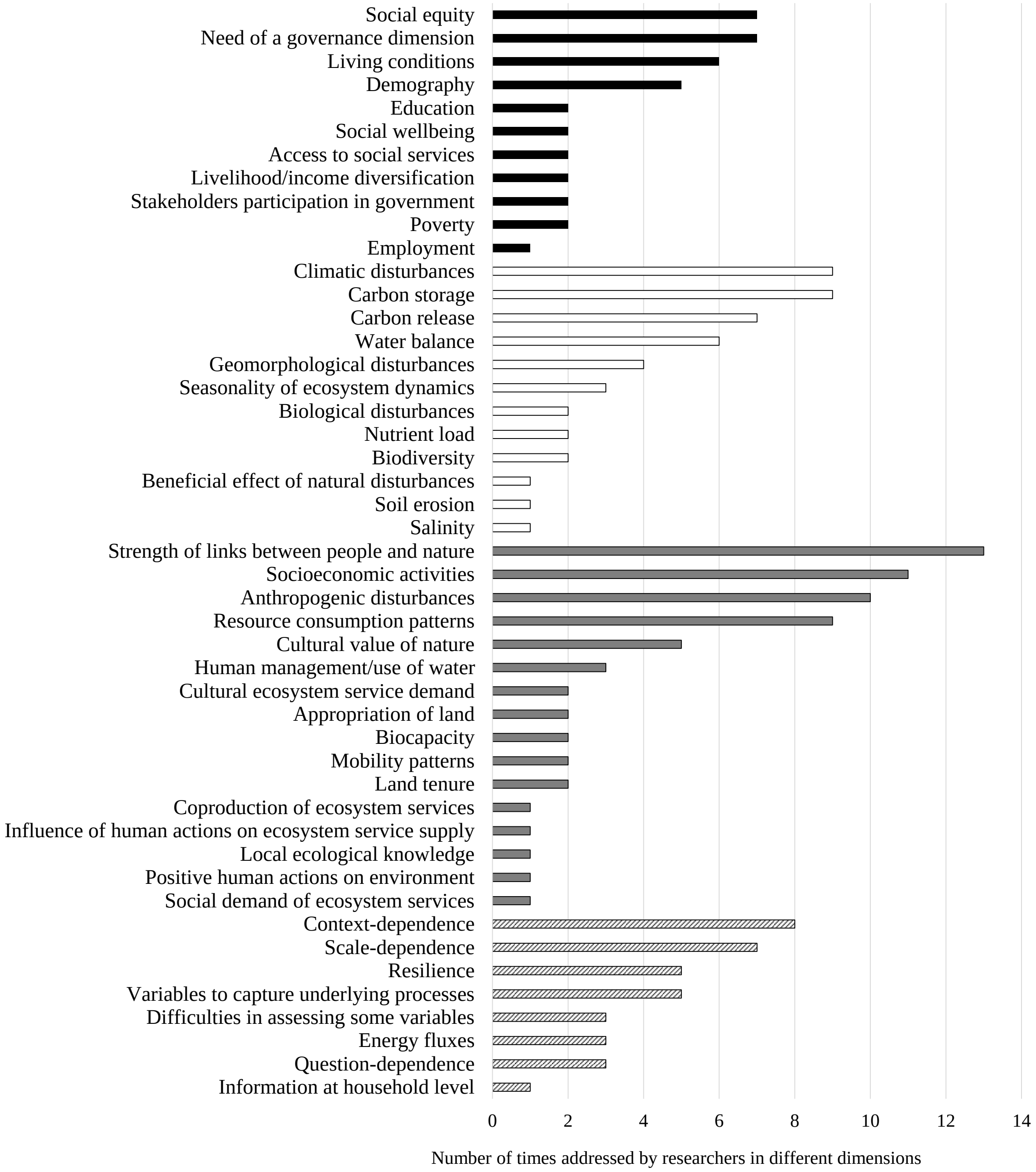
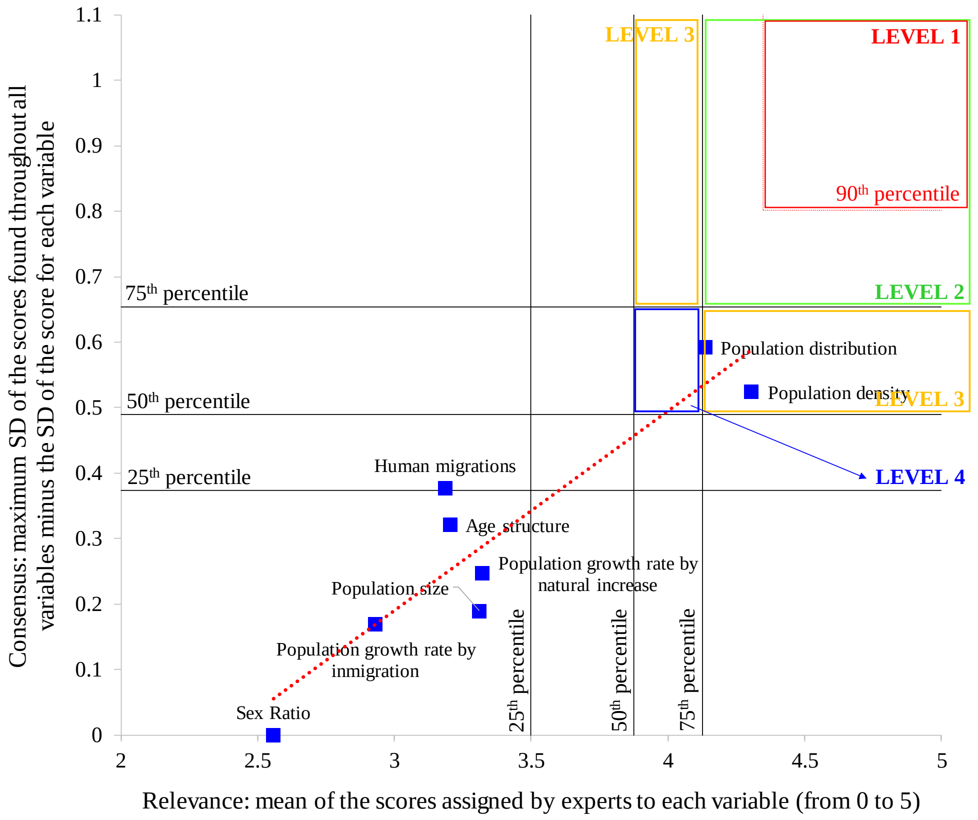


Fig. F1. Featured topics identified from suggestions and comments in the preliminary survey, which were used to improve the preliminary list of variables and dimensions for characterizing and monitoring SES. Black, white and gray bars represent the social system, ecological system and interaction components, respectively, while stripped bars reflect issues that are transversal to the whole conceptual framework. (See also these topics in the conceptual map of Appendix 7).

Fig. F2 to F14. Detail view of the relationship between average relevance and consensus obtained by the variables belonging to each dimension of social-ecological system functioning. Relevance was evaluated as the mean of the scores assigned by experts to each variable. The consensus was estimated as the difference between the maximum standard deviation of the scores found throughout the 149 variables and the standard deviation of the score for each variable (low differences indicated low consensus and high differences, high consensus). Horizontal and vertical lines represent the 25th, 50th, 75th and 90th percentiles of relevance and consensus for the whole set of variables belonging to the 13 dimensions of social-ecological functioning. Boxes over the grid illustrate the clustering of the variables by priority levels. The red box (priority level 1) includes those variables with relevance and consensus above the 90th percentile; the green box (level 2) includes those variables with both values between the 75th and 90th percentiles; the yellow box (level 3) includes those with relevance above the 75th percentile but consensus between the 50th and 75th percentiles and vice versa; and the blue box (level 4) includes variables with relevance and consensus between the 50th and 75th percentiles. At the bottom right of each figure, the equation of the regression line, the significance of the line slope (p-value) and the root-mean-square error (RMSE) are indicated, as are the number of variables (n), the Spearman's correlation coefficient (r) and its significance (p-value)).



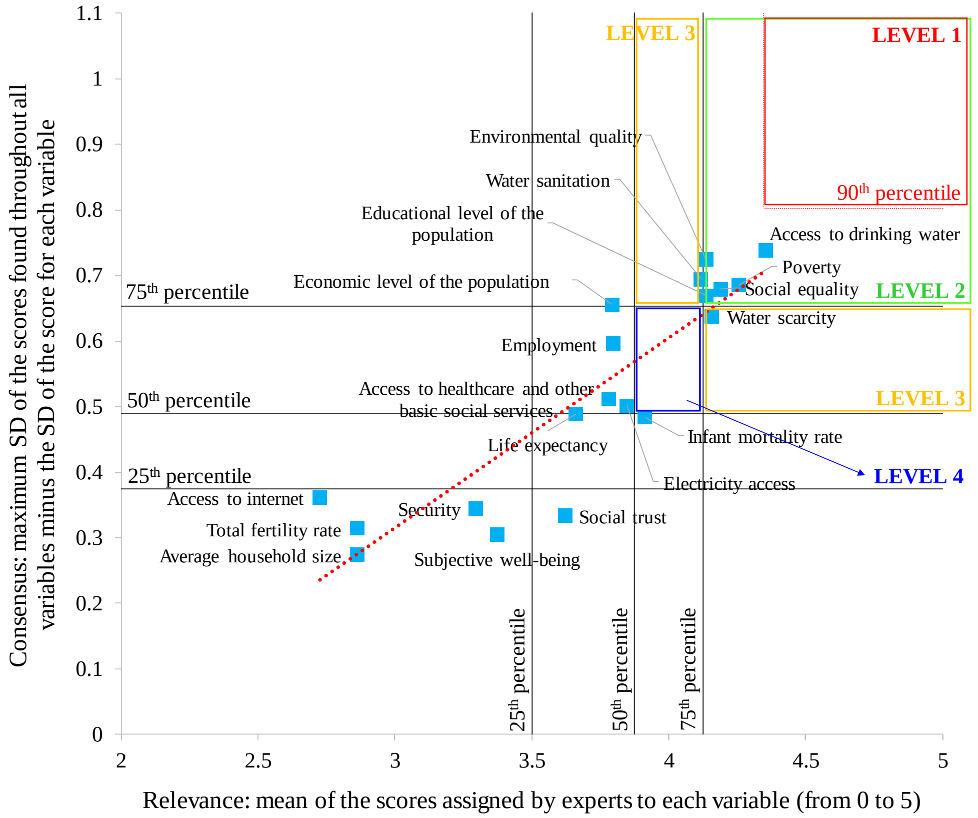
F2

Component: social system
Dimension: human population dynamics

····· Regression line

y = - 0.73 + 0.31x
p-value =0.001
RMSE = 0.07

n = 8; r = 0.76
p-value = 0.037

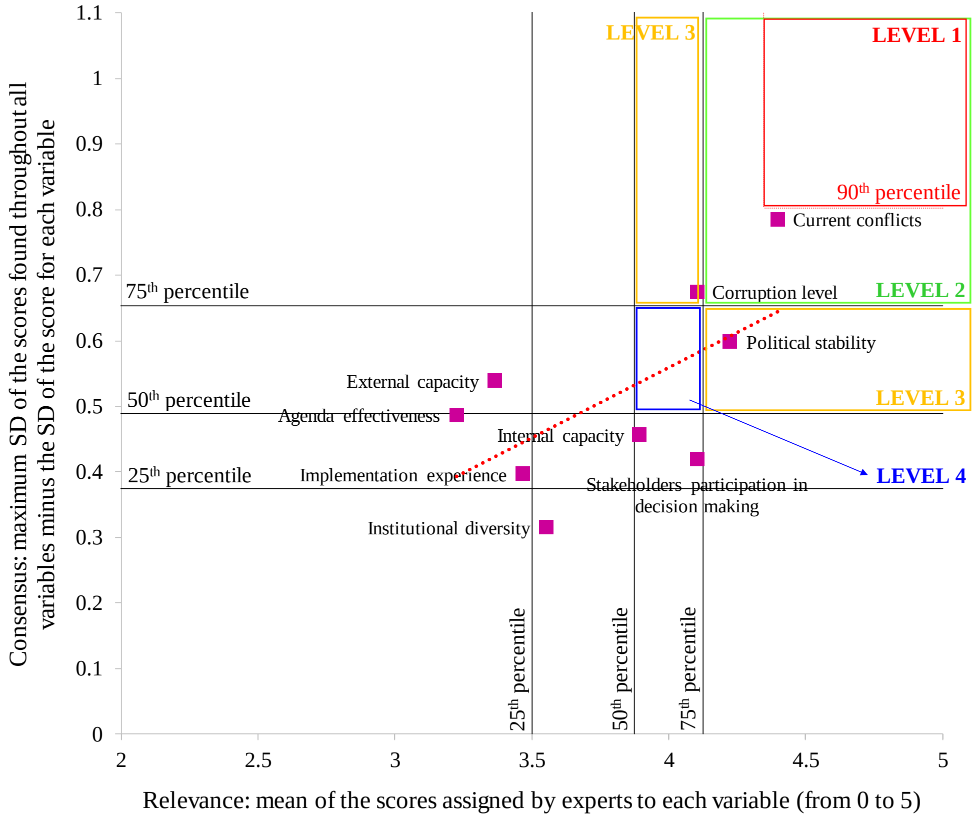


F3

Component: social system
Dimension: wellbeing and development

Regression line
y = - 0.55 + 0.29x
p-value < 0.001
RMSE = 0.07

n = 19; r = 0.87
p-value < 0.001



F4

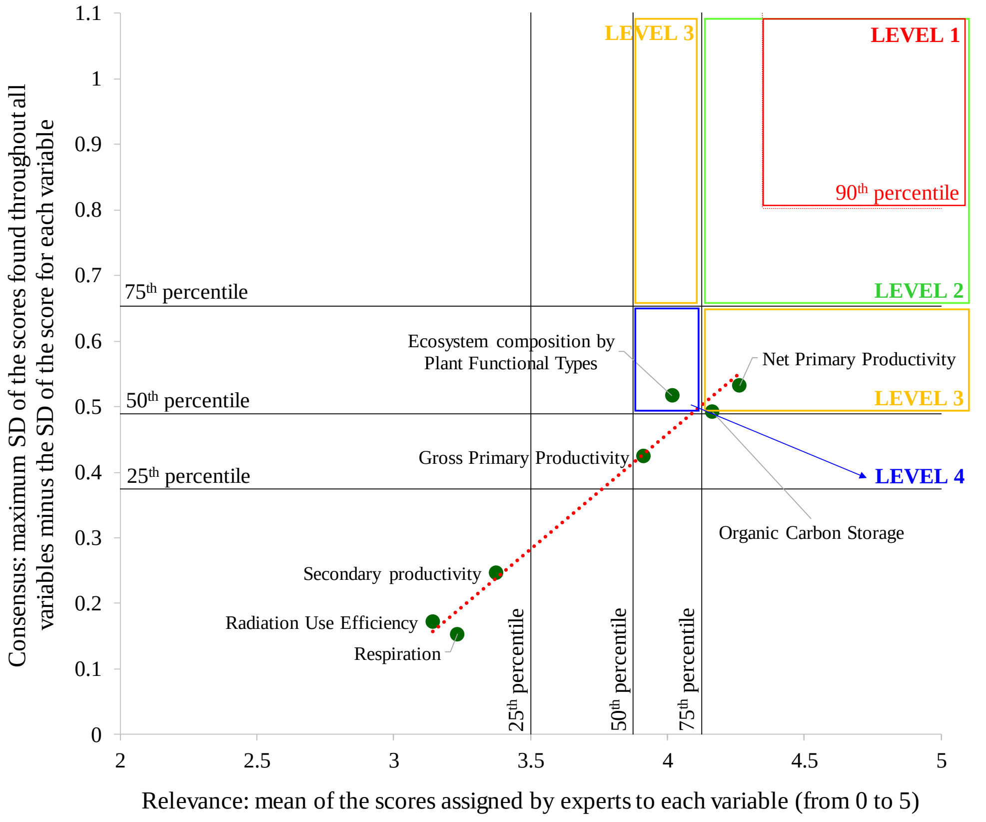
Component: social system
Dimension: governance

Regression line
y = - 0.30 + 0.21x
p-value = 0.079
RMSE = 0.11

n = 9; r = 0.51
p-value = 0.160

F5

Component: ecological system
Dimension: organic carbon dynamics

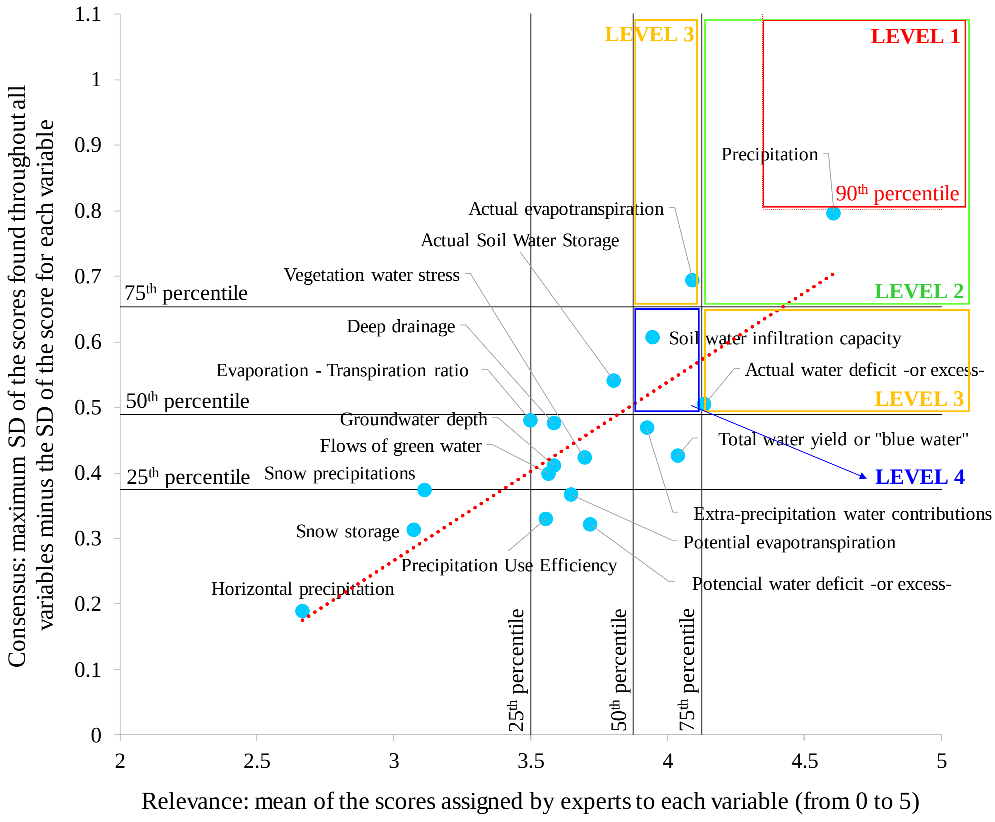


Regression line
y = - 0.95 + 0.35x
p-value < 0.001
RMSE = 0.03

n = 7; r = 0.93
p-value = 0.007

F6

Component: ecological system
Dimension: water dynamics

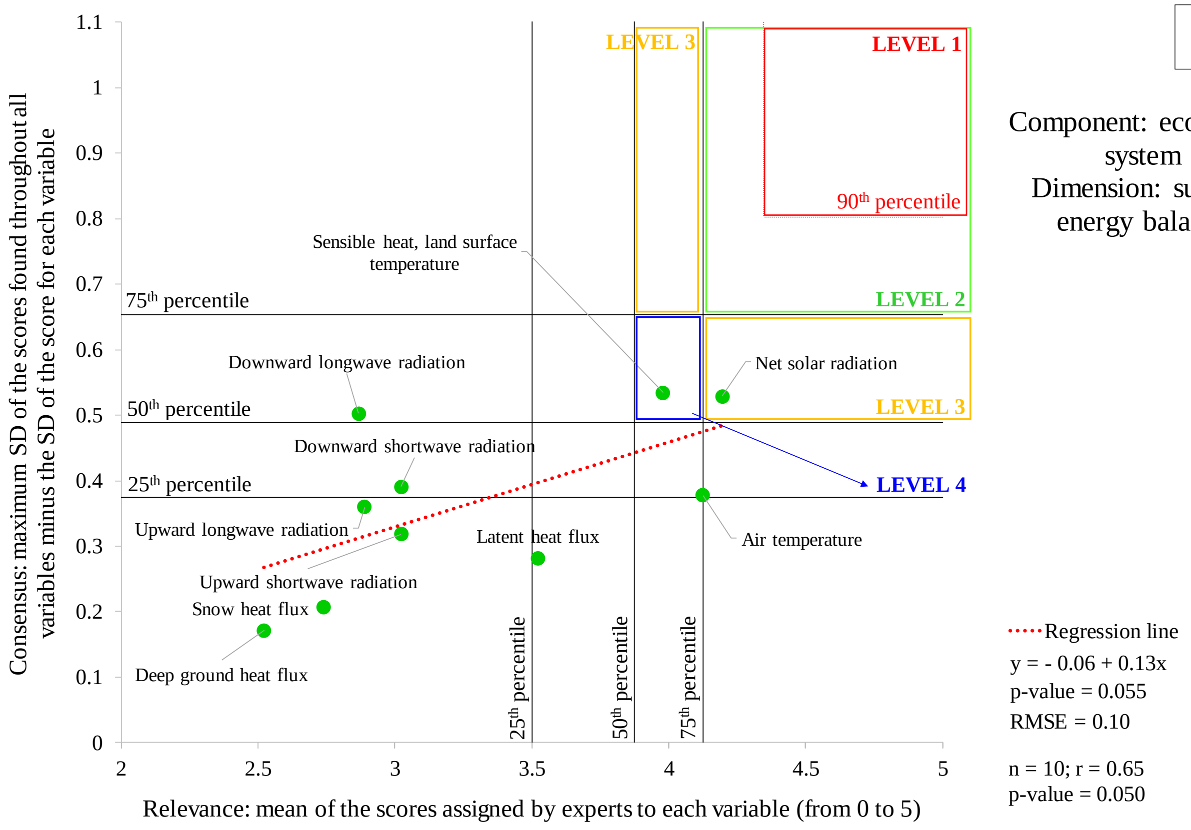


Regression line
y = - 0.55 + 0.27x
p-value < 0.001
RMSE = 0.08

n = 18; r = 0.75
p-value < 0.001

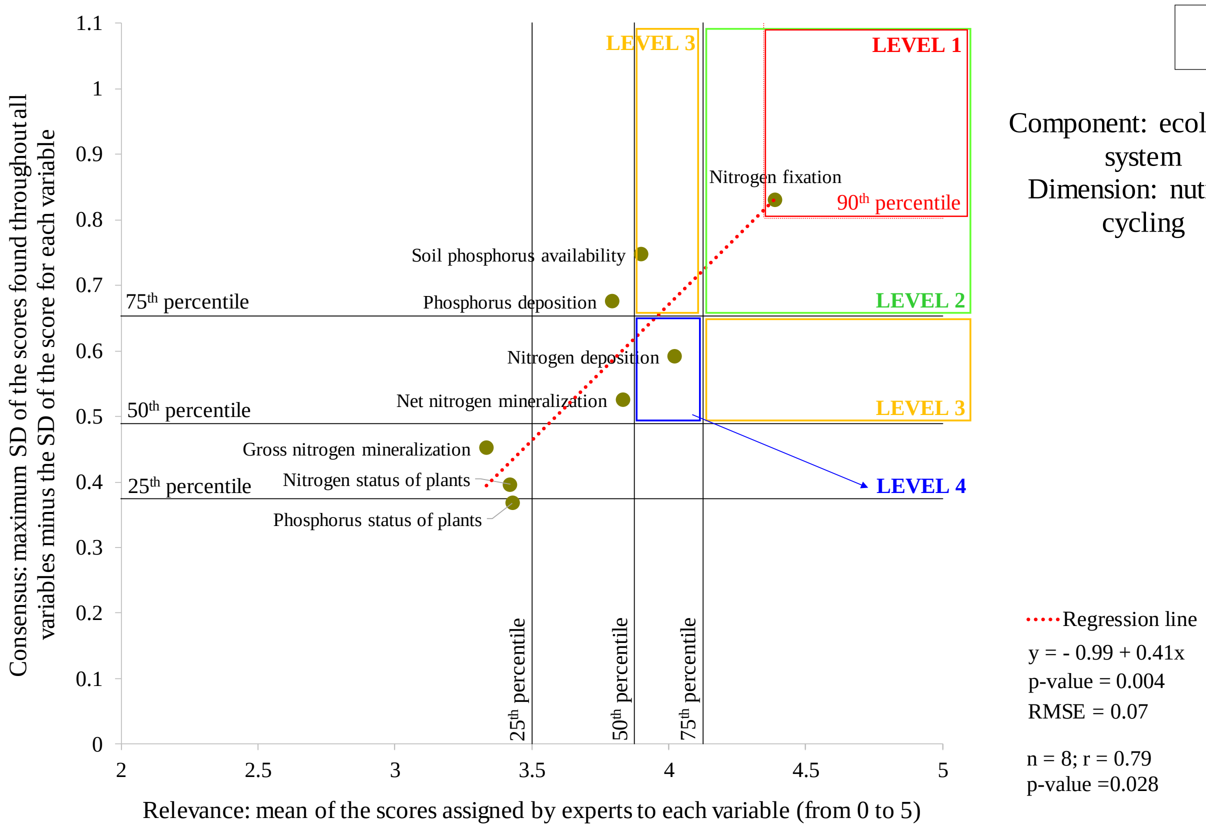
F7

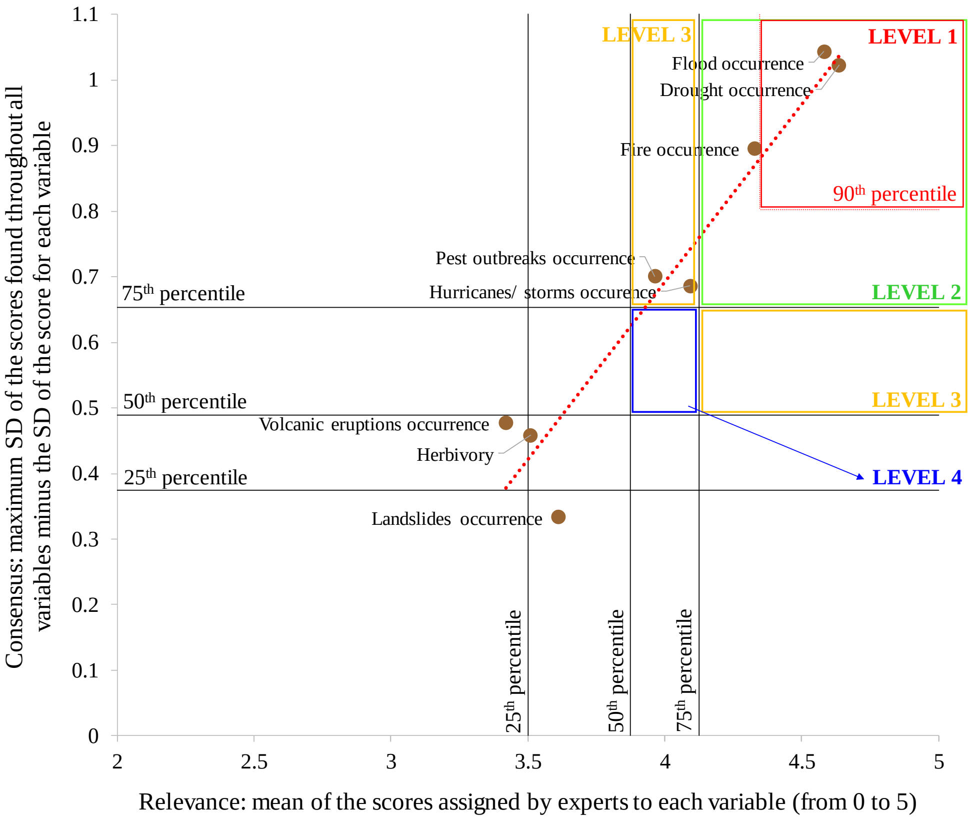
Component: ecological system
Dimension: surface energy balance



F8

Component: ecological system
Dimension: nutrient cycling



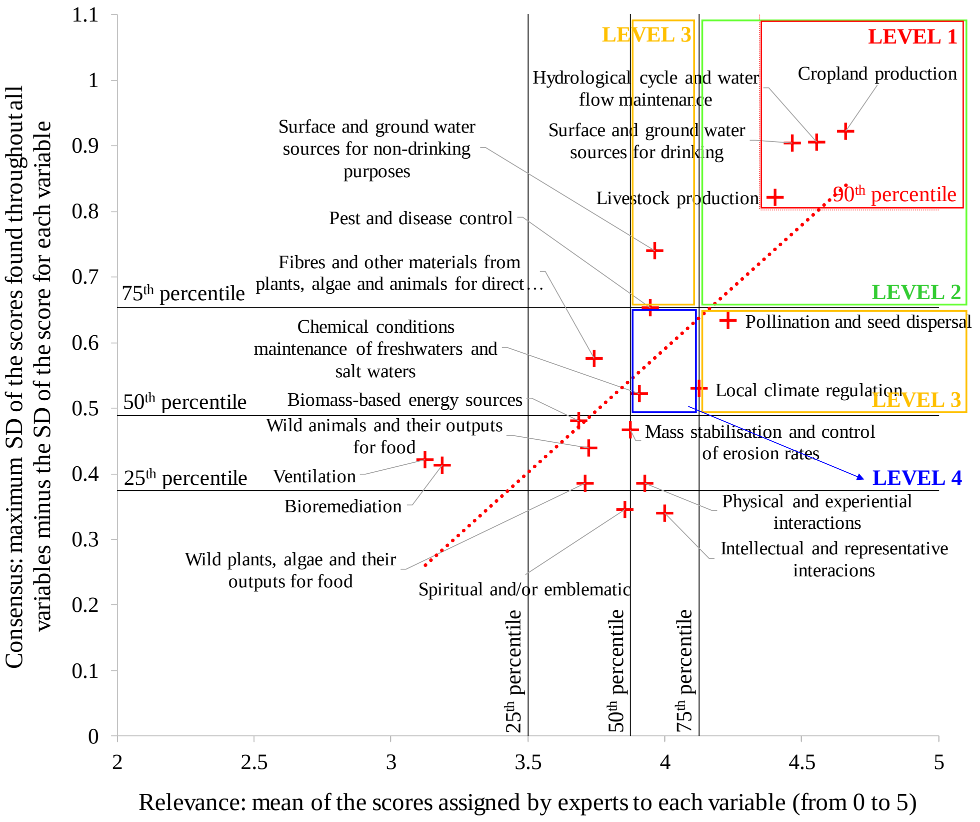


F9

Component: ecological system
Dimension: disturbance regime

Regression line
y = - 1.47 + 0.54x
p-value < 0.001
RMSE = 0.07

n = 8; r = 0.86
p-value = 0.011

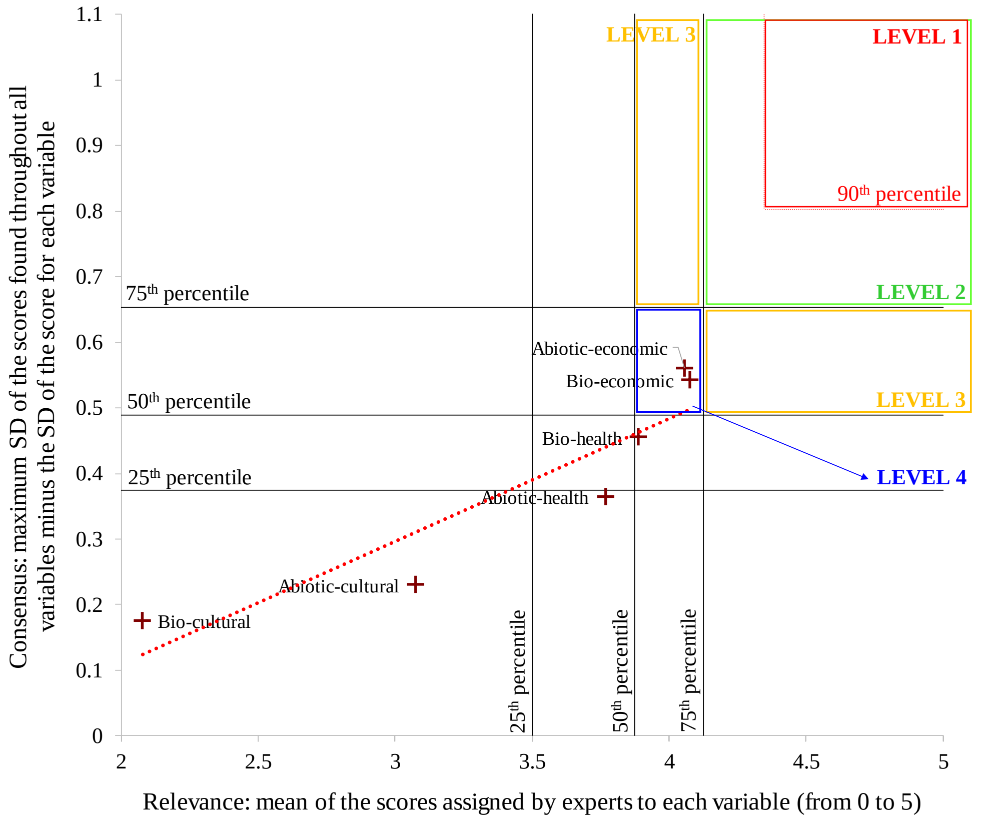


F10

Component: interactions
Dimension: ecosystem service supply

Regression line
y = - 0.92 + 0.38x
p-value < 0.001
RMSE = 0.12

n = 19; r = 0.69
p-value = 0.001

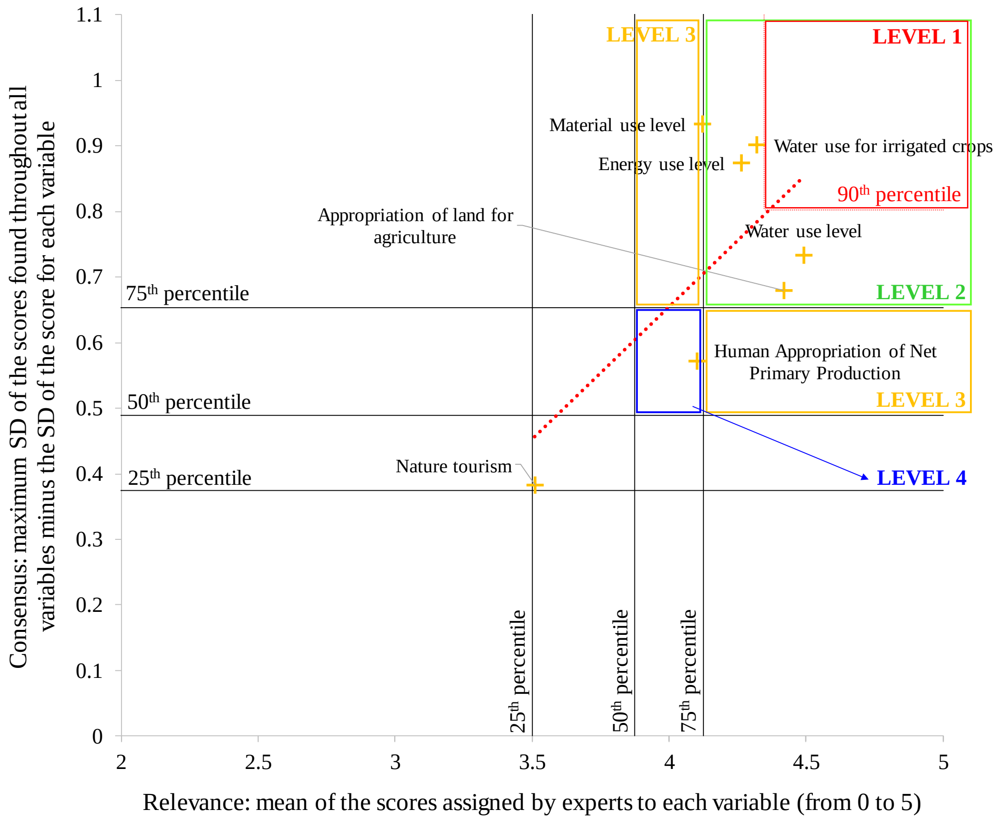


F11

Component: interactions
Dimension: ecosystem disservice supply

Regression line
$y = -0.26 + 0.19x$
p-value = 0.011
RMSE = 0.06

n = 6; r = 0.94
p-value = 0.017

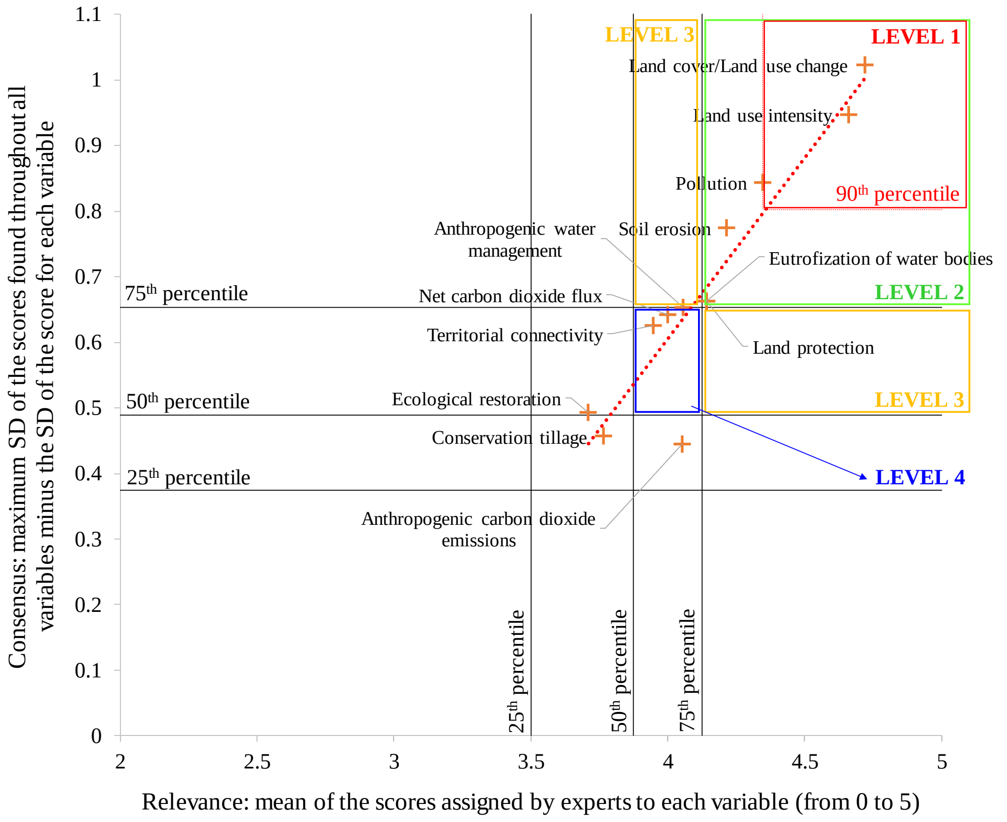


F12

Component: interactions
Dimension: ecosystem service demand

Regression line
$y = -0.96 + 0.40x$
p-value = 0.107
RMSE = 0.14

n = 7; r = 0.36
p-value =0.444

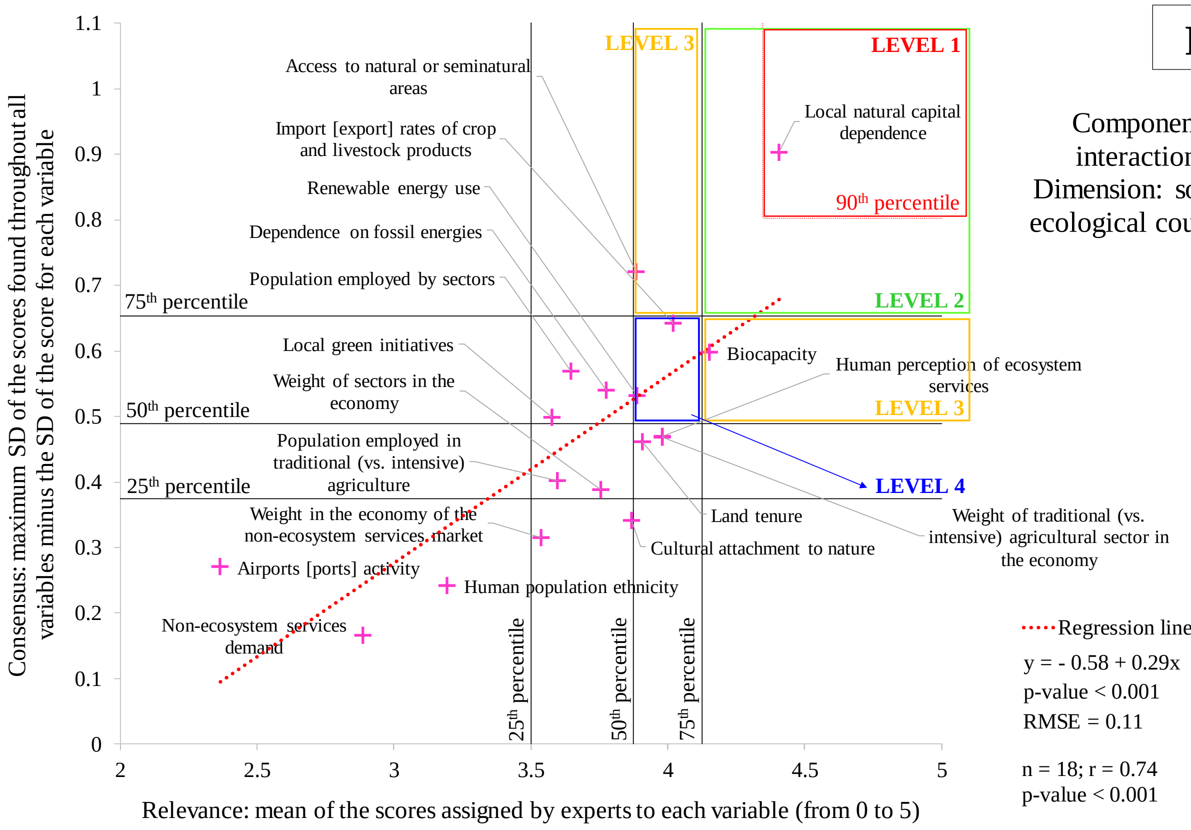


F13

Component: interactions
Dimension: human actions on the environment

Regression line
$y = -1.60 + 0.55x$
p-value < 0.001
RMSE = 0.06

n = 12; r = 0.92
p-value < 0.001



F14

Component: interactions
Dimension: social-ecological coupling

Regression line
$y = -0.58 + 0.29x$
p-value < 0.001
RMSE = 0.11

n = 18; r = 0.74
p-value < 0.001

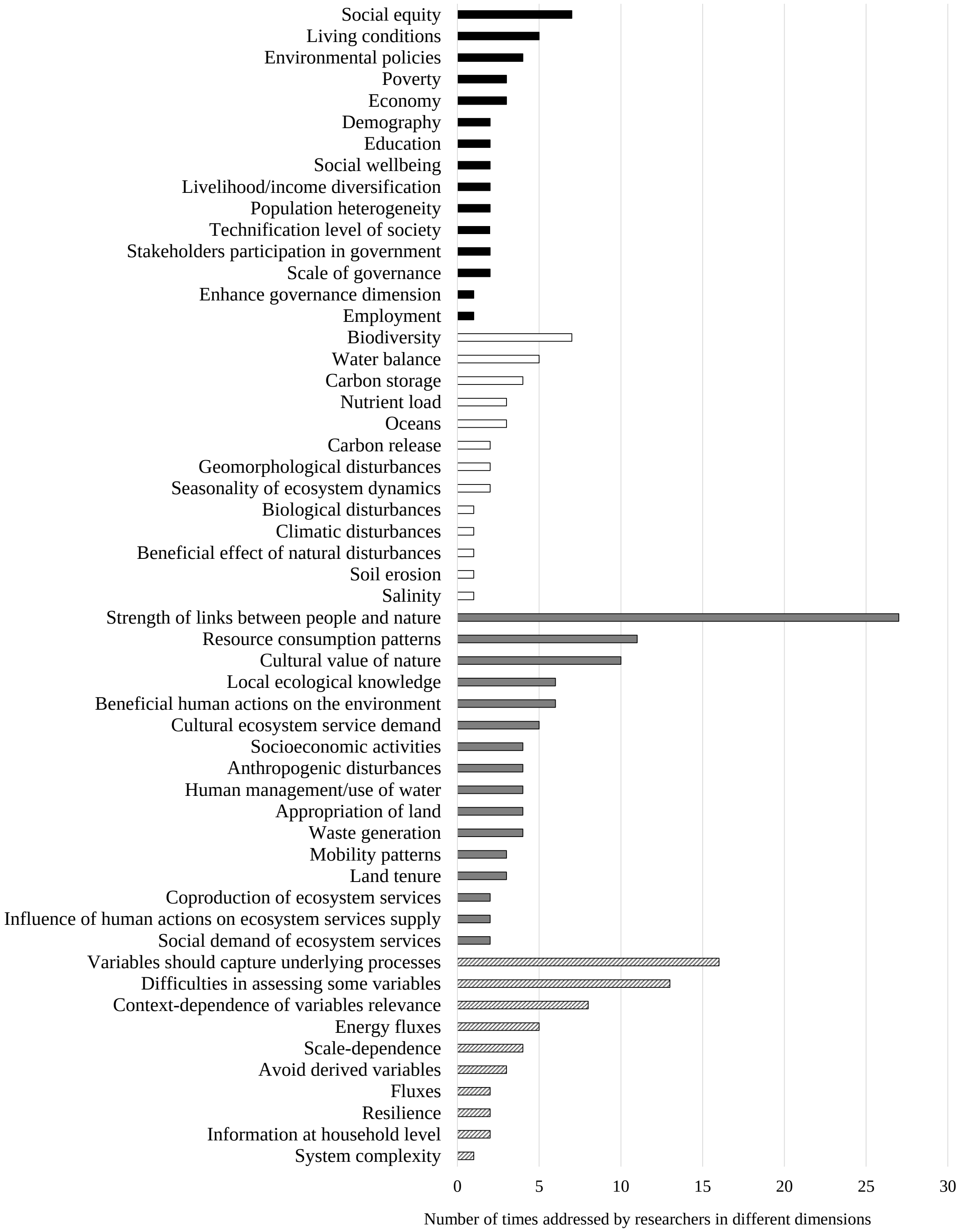


Fig. F15. Extended version of Fig. 4 in the manuscript. Featured topics addressed by respondents related to potential biases and gaps in the list of variables identified from comments and suggestions in the final survey. Black, white, and gray bars represent the social system, ecological system and interaction components, respectively, while stripped bars reflect issues that are transversal to the whole conceptual framework. (See also these topics in the conceptual map of Appendix G).

Appendix 1G. Conceptual map with keywords annotated from comments and suggestions provided by respondents in both surveys

Please, see the online version at: https://doi.org/10.5751/ES-11676-250301 (Appendix7)

Appendix 1H. Detailed results of the relevance and consensus obtained for each variable

Please, download the Excel table at: https://doi.org/10.5751/ES-11676-250301 (Appendix8)

Appendix 1I. Acknowledgement to survey respondents.

We gratefully acknowledge the participation in the preliminary survey to:

Last name	First name	Institution/Department	Area of expertise
Açma	Bülent	Anadolu University - Department of Economy (Turkey)	Social sciences Sustainability Science Environmental management / Territorial planning
Balvanera	Patricia	Universidad Nacional Autónoma de México - Instituto de Investigaciones en Ecosistemas y Sustentabilidad (Mexico)	Biophysical sciences Sustainability Science Environmental management / Territorial planning Biodiversity Science Ecosystem services Social-ecological systems
Bentley-Brymer	Amanda	University of Idaho - Rangeland Center (USA)	Social sciences Environmental management / Territorial planning
Brown	Dan	University of Michigan - Graham Sustainability Institute (USA)	Sustainability Science Environmental management / Territorial planning Remote sensing
Chapin	Terry	University of Alaska Fairbanks - Institute of Arctic Biology (USA)	Sustainability Science
Ellis	Erle	University of Maryland Baltimore County - Geography & Environmental Systems (USA)	Biophysical sciences Sustainability Science Environmental management / Territorial planning Remote sensing Biodiversity Science
Escribano-Velasco	Paula	Andalusian Center for the Assessment and Monitoring of Global Change – University of Almería (Spain)	Environmental management / Territorial planning Remote sensing
Fabricius	Christo	Nelson Mandela University - Sustainability Research Unit (South Africa)	Sustainability Science
García-Nieto	Ana Paula	Mediterranean Institute of marine and terrestrial Biodiversity and Ecology (France)	Ecology

Garcia-Valdecasas	José Ignacio	University Carlos III de Madrid – Department of Social Sciences (Spain)	Social sciences
Gibout	Christophe	Université du Littoral Côte d'Opale (France)	Social sciences
Golland	Ami	Stockholm University - Stockholm Resilience Centre (Sweden)	Sustainability Science Electronic engineering
Hernandez-Zamorano	Isaac Rhodart	Universidad Nacional Autónoma de México - National School of Higher Studies Morelia (Mexico)	Enviromental Science
Hevia	Glenda Denise	Centre for Studies on Marine Systems, CESIMAR - CCT CENPAT- CONICET (Argentina)	Environmental management / Territorial planning Biodiversity Science Avian breeding biology
Hinton	Jennifer	Stockholm University - Stockholm Resilience Centre (Sweden)	Social sciences Sustainability Science
Ignatov	Alex	Russian University of People's Friendship - R&D Center PhytoEngineering LLC (Russia)	Sustainability Science Biodiversity Science
Leitão	Pedro J.	Technische Universität Braunschweig - Department of Landscape Ecology and Environmental Systems Analysis (Germany)	Remote sensing Biodiversity Science
Locatelli	Bruno	University of Montpellier - Forests and Societies research unit - CIRAD (France)	Sustainability Science
Martin	Romina	Stockholm University - Stockholm Resilience Centre (Sweden)	Sustainability Science
Martinez-Harms	Maria Jose	Pontifical Catholic University of Chile – Department of Ecology (Chile)	Sustainability Science Environmental management / Territorial planning Biodiversity Science
Martin-Lopez	Berta	Leuphana University of Luneburg - Institute for Ethics and Transdisciplinary	Sustainability Science

		Sustainability Research (Germany)	
Nagendra	Harini	Azim Premji University - School of Development (India)	Sustainability Science Remote sensing Biodiversity Science
Narducci	Jenna	Boise State University – Department of Geosciences (USA)	Environmental management / Territorial planning
Niquil	Nathalie	French National Centre for Scientific Research - Institut écologie et environnement (France)	Biodiversity Science Ecology
Noss	Reed	Florida Institute for Conservation Science (USA)	Environmental management / Territorial planning, Biodiversity Science
Pandey	Rajiv	Indian Council of Forestry Research &Education (India)	Vulnerability and Adaptation in Social-ecological systems
Pardo	Mercedes	University Carlos III de Madrid - Sociology of Climate Change and Sustainable Development (Spain)	Social sciences
Rodríguez	Jon Paul	Instituto Venezolano de Investigaciones Científicas - Centro de Ecología (Venezuela)	Biodiversity Science
Romero-Calcerrada	Raúl	King Juan Carlos University – Faculty of Legal and Social Sciences (Spain)	Environmental management / Territorial planning Remote sensing
Ruggeri	Daniela	University of Cagliari - Dipartimento di Ingegneria Civile, Ambientale e Architettura (Italy)	Environmental management / Territorial planning
Vallet	Améline	AgroParisTech – CIRED (France)	Biophysical sciences Social sciences

… and to 25 additional researchers who anonymously filled the preliminary survey

We also gratefully acknowledge the participation in the final survey to:

Last name	First name	Institution/Department	Area of expertise
Baró	Francesc	Autonomous University of Barcelona - Institute of Environmental Sciences and Technologies (Spain)	Sustainability Science Environmental management / Territorial planning
Berbery	E. Hugo	University of Maryland - Earth System Science Interdisciplinary Center (USA)	Climate Sciences
Blenckner	Thorsten	Stockholm University - Stockholm Resilience Centre (Sweden)	Biophysical sciences Sustainability Science Biodiversity Science
Blum	Alfredo	Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente (Uruguay)	Social sciences Sustainability Science Environmental management / Territorial planning
Castro	Antonio J.	University of Almería - Department of Biology and Geology (Spain)	Biophysical sciences Social sciences Sustainability Science
Ceausu	Silvia	Aarhus University - Department of Bioscience (Denmark)	Environmental management / Territorial planning Biodiversity Science
Couvet	Denis	Muséum National d'Histoire Naturelle (France)	Biodiversity Science
Felipe-Lucia	María	Helmholtz Centre for Environmental Research - Centre for Integrative Biodiversity Research (iDiv) (Germany)	Biophysical sciences Social sciences Sustainability Science Environmental management / Territorial planning Biodiversity Science Ecosystem services
Filatova	Tatiana	University of Twente - Department of Governance and Technology for Sustainable Development (The Netherlands)	Social sciences Sustainability Science Environmental management / Territorial planning
Fischer-Kowalski	Marina	University of Natural Resources and Life Sciences Vienna - Institute of Social Ecology (Austria)	Social sciences Sustainability Science
Furman	Eeva	Finnish Environment Institute | ymparisto -	Social sciences Sustainability Science

		Centre for Environmental Policy (Finland)	Environmental management / Territorial planning Biodiversity Science
Garcia del Amo	David	Autonomous University of Barcelona - Institute of Environmental Sciences and Technologies (Spain)	Sustainability Science
Geijzendorffer	Ilse	Tour du Valat - Research Institute for the conservation of Mediterranean Wetlands (France)	Biophysical sciences Sustainability Science Environmental management / Territorial planning Biodiversity Science Ecosystem services
Ifejika Speranza	Chinwe	Universität Bern - Centre for Development and Environment - Institute of Geography (Switzerland)	Sustainability Science
López-Rodríguez	María D.	University of Almeria - Andalusian Center for the Assessment and Monitoring of Global Change (Spain)	Sustainability Science
Luque	Sandra	National Research Institute of Science and Technology for Environment and Agriculture - UMR TETIS Territoires, Environnement, Télédétection et Information Spatiale (France)	Biophysical sciences Sustainability Science Environmental management / Territorial planning Remote sensing Biodiversity Science
Macchi	Leandro	CONICET - Instituto de Ecología Regional (IER) - Universidad Nacional de Tucumán (Argentina)	Sustainability Science Biodiversity Science
Mahecha	Miguel	Max Planck Institute for Biogeochemistry - Department of Biogeochemical Integration (Germany)	Biophysical sciences Sustainability Science Remote sensing Biodiversity Science
Martinez-Harms	Maria Jose	Pontifical Catholic University of Chile – Department of Ecology (Chile)	Sustainability Science Environmental management / Territorial planning Biodiversity Science
Munday Seguel	Daniel	Economic Commission for Latin America and the Caribbean (Chile)	Environmental management / Territorial planning

Onaindia	Miren	University of the Basque Country – Department of Plant Biology and Ecology (Spain)	Biophysical sciences Environmental management / Territorial planning Biodiversity Science
Ozán	Ivana	CONICET - Instituto de Geociencias Básicas, Ambientales y Aplicadas de Buenos Aires (Argentina)	Social sciences Geoarchaeology
Piñeiro	Gervasio	Universidad de Buenos Aires - Facultad de Agronomía (Argentina)	Biophysical sciences Remote sensing
Requena	Juan Miguel	Boise State University - Department of Biological Sciences (USA)	Remote sensing Biodiversity Science
Roche	Philip	National Research Institute of Science and Technology for Environment and Agriculture IRSTEA - Lands Department (France)	Remote sensing Biodiversity Science
Rosales Benites de Franco	Marina	Federico Villarreal National University - Biological Sciences (Peru)	Biodiversity Science
Saldivar	Americo	Universidad Nacional Autónoma de México – Faculty of Economy (Mexico)	
Volk	Martin	UFZ-Helmholtz Centre for Environmental Research - Department of Computational Landscape Ecology (Germany)	Biophysical sciences Sustainability Science Environmental management / Territorial planning Biodiversity Science
Watmough	Gary	The University of Edinburgh - School of GeoSciences (UK)	Sustainability Science Remote sensing

… and to 30 additional researchers who anonymously filled the final survey

Apéndices del resultado 2.2

Appendix 2A. Indicators

Table A1. Indicators (structured per social-ecological system components, dimensions and variables) used in the methodological routine for the detection and mapping of social-ecological systems. *Superscript letter indicates the outcomes of the database screening process: a = indicators selected for SES mapping; b = indicators discarded for being the least relevant among the correlated ones; c = indicators discarded for being the least relevant from the database.

Variable	Indicator	ID*	Unit	Year	Resolution	Source
Social system						
Human population dynamics (PD)						
Population density	Population density	PD_1[a]	People km^{-2}	2016	municipality	SIMA
Population distribution	Population dispersion	PD_2[a]	%	2016	municipality	SIMA
Population ageing	Population mean age	PD_3[a]	Years	2016	municipality	SIMA
	Population ageing index	PD_4[b]	Index	2016	municipality	SIMA
Natural population growth	Rate of natural increase	PD_5[b]	Index	2016	municipality	SIMA
Migrations	Net migration rate	PD_6[c]	Index	2016	municipality	SIMA
Well-being and development (WB)						
Educational level	Population over 15 with less than 5 years of school attendance	WB_1[b]	%	2011	municipality	SIMA
Employment	Unemployment rate	WB_2[a]	%	2016	municipality	SIMA

	New employment temporary contracts	WB_3[c]	%	2016	municipality	SIMA
Economic level	Mean income	WB_4[a]	€ contributor^{-1} year^{-1}	2015	municipality	SIMA
Social equity	Women farm owners	WB_5[c]	%	2009	municipality	SIMA
	Female unemployment rate	WB_6[c]	% (over unemployed population)	2016	municipality	SIMA
Dependency	Pensioner rate	WB_7[b]	% (over active population)	2016	municipality	SIMA
	Child dependency ratio	WB_8[b]	%	2016	municipality	SIMA
	Aged dependency ratio	WB_9[b]	%	2016	municipality	SIMA
Access to healthcare and other basic social services	Mean pension	WB_10[b]	€ pensioner^{-1} month^{-1}	2016	municipality	SIMA
	Mean pension (non-contributory)	WB_11[c]	€ pensioner^{-1} month^{-1}	2015	municipality	SIMA
<u>Governance (G)</u>						
Participation	Turnout in local elections	G_1[c]	%	2015	municipality	SIMA
Internal capacity of the government	Surplus or deficit in local accounts	G_2[c]	€ inhabitant^{-1} year^{-1}	2015	municipality	SIMA
	Public expenditure	G_3[c]	€ inhabitant^{-1} year^{-1}	2015	municipality	SIMA
	Tax burden	G_4[c]	€ inhabitant^{-1} year^{-1}	2015	municipality	SIMA
	Agricultural subsidies (CAP payments)	G_5[a]	€ beneficiary^{-1} year^{-1}	2016	municipality	FEGA
Land protection	Natural protected area	G_6[a]	%	2007	municipality	SIMA
Ecological System						

Organic carbon dynamics (OCD)						
Net Primary Productivity	Mean annual EVI	OCD_1[b]	Index	2001-2014	raster (230 m)	NASA-MODIS
Seasonality	CV annual EVI	OCD_2[a]	Index	2001-2014	raster (230 m)	NASA-MODIS
Water dynamics (WD)						
Precipitation	Mean annual precipitation	WD_1[a]	mm year^{-1}	1971-2000	raster (100 m)	REDIAM
Actual evapotranspiration	Mean annual potential evapotranspiration	WD_2[b]	mm year^{-1}	1971-2000	raster (100 m)	REDIAM
Actual water deficit or excess	Moisture index (P/PET)	WD_3[b]	Index	1971-2000	raster (100 m)	REDIAM
Surface energy balance (SEB)						
Net solar radiation	Net solar radiation	SEB_1[a]	kW m^{-2} year^{-1}	2010	raster (250 m)	REDIAM
Air temperature	Mean annual temperature	SEB_2[a]	ºC	1971-2000	raster (100 m)	REDIAM
Disturbance regime (DR)						
Drought occurrence	Mean drought standardised index	DR_1[c]	Index	2000-2012	raster (1000 m)	REDIAM
Fire occurrence	Forest fires recurrence	DR_2[c]	Fires year^{-1}	1975-2016	shape (polygon)	REDIAM
	Burned surface	DR_3[c]	%	1975-2016	shape (polygon)	REDIAM
Desertification	Desertification rate (desertified or near to desertification area)	DR_4[a]	%	2004	raster (80 m)	REDIAM
Rainfall torrentiality	Rainfall maximum torrentiality (from average monthly torrentiality)	DR_5[c]	%	1996-2016	raster (1000 m)	REDIAM

Soil erosion	Mean annual rain erosivity	DR_6[b]	MJ mm ha^{-1} hour^{-1} year^{-1}	1976-2005	raster (75 m)	REDIAM
	Soil erosion rate (area with high annual mean erosion)	DR_7[a]	%	1992-2014	municipality	SIMA
Interactions						
<u>Ecosystem service supply (ESS)</u>						
Cultivated crops (P)	Crop production	ESS_1[a]	Ton ha^{-1} year^{-1}	2015	municipality	SIMA
Reared animals and their outputs (P)	Livestock production	ESS_2[a]	Livestock units ha^{-1}	2009	municipality	SIMA
	Beekeeping	ESS_3[c]	Hives ha^{-1}	2009	municipality	SIMA
Wild animals and their outputs (P)	Fishing	ESS_4[c]	CPUE (Ton kW^{-1} year^{-1})	2011	municipality	SIMA
Mass stabilisation and control of erosion rates (R)	Mean annual protection of vegetation cover against erosion	ESS_5[b]	Index	2002	raster (188 m)	REDIAM
	Runoff	ESS_6[b]	Index	2007	raster (20 m)	REDIAM
Pollination (R)	Optimal suitability area for beekeeping	ESS_7[a]	%	2005	raster (100 m)	REDIAM
Maintaining nursery populations and habitats (R)	Phytocenotic diversity	ESS_8[b]	Index	2005	raster (80 m)	REDIAM
Global climate regulation by reduction of greenhouse gas concentrations (R)	Carbon sequestration by terrestrial ecosystems	ESS_9[a]	Ton ha^{-1}	2013	municipality	REDIAM
Physical and experiential interactions (C)	Landscape diversity	ESS_10[a]	Index	2009	shape (polygon)	REDIAM
	Landscape naturalness	ESS_11[b]	Index	2009	shape (polygon)	REDIAM

	Public use facilities in natural areas	ESS_12^{c}	Number of facilities ha^{-1}	2013	shape (polygon)	REDIAM
Intellectual and representative interactions (C)	Habitats of Community Interest (HCI) area	ESS_13^{b}	%	2016	raster (50 m)	REDIAM
	Mean richness of HCI	ESS_14^{b}	Number of HCI	2016	raster (50 m)	REDIAM
Ecosystem service demand (ESD)						
Appropriation of land for agriculture	Cropland area	ESD_1^{b}	%	2013	municipality	SIMA
Water use level	GHG emissions in wastewater treatment	ESD_2^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
Energy use level	CO_2 emissions in energy consumption (total)	ESD_3^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	CO_2 emissions in energy consumption (agriculture)	ESD_4^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	CO_2 emissions in energy consumption (industry)	ESD_5^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	CO_2 emissions in energy consumption (service sector)	ESD_6^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	CO_2 emissions in energy consumption (residential sector)	ESD_7^{c}	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
Human actions on the environment (HAE)						
Land use/land cover	Artificial surface	HAE_1^{b}	%	2013	municipality	SIMA
	Natural surface	HAE_2^{a}	%	2013	municipality	SIMA

Land use intensity	Cropland productivity	HAE_3[a]	Ton cropland_ha^{-1} year^{-1}	2015	municipality	SIMA
	Irrigated cropland area	HAE_4[b]	% (of total cropping area)	2015	municipality	SIMA
	Livestock density	HAE_5[c]	Livestock units grazing_ha^{-1}	2009	municipality	SIMA
	Area with high agricultural nitrogen input	HAE_6[c]	%	2009	shape (polygon)	REDIAM
Urban waste production	GHG emissions in urban waste treatment	HAE_7[a]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
Environmental quality	Night sky quality	HAE_8[a]	Magnit arcseg $^{-2}$	2015	raster (100 m)	REDIAM
	Fleet	HAE_9[c]	Vehicles inhabitant^{-1}	2015	municipality	SIMA
	CO$_2$ emissions by fleet	HAE_10[b]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
Anthropogenic greenhouse gas emission	Total GHG emissions	HAE_11[a]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	GHG emissions by crop production	HAE_12[c]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	GHG emissions by livestock production	HAE_13[c]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
	CO$_2$ emissions by other fossil fuels	HAE_14[c]	Ton CO$_2$eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM
Territorial connectivity	Distance to capital city	HAE_15[a]	Km	2014	municipality	SIMA
Social-ecological (de)coupling (SEC)						
Local natural capital dependence	Employments in agriculture	SEC_1[a]	%	2009	municipality	SIMA
	New employments in agriculture	SEC_2[a]	%	2016	municipality	SIMA

	New employments in agriculture + industry	SEC_3[b]	%	2016	municipality	SIMA
	New employments in service sector	SEC_4[b]	%	2016	municipality	SIMA
Traditional/organic agriculture	Organic livestock production	SEC_5[c]	% (of total livestock units)	2009	municipality	SIMA
	Organic crop production	SEC_6[c]	% (of total agricultural area)	2009	municipality	SIMA
	Rainfed crop production	SEC_7[a]	% (of total agricultural production)	2015	municipality	SIMA
Local green initiatives	Farms with rural development activities	SEC_8[c]	%	2009	municipality	SIMA
Land tenure	Agricultural area under cooperative management	SEC_9[c]	%	2009	municipality	SIMA
	Average farm area	SEC_10[a]	Ha	2009	municipality	SIMA
	Young farm owners (< 44)	SEC_11[c]	%	2009	municipality	SIMA
Transport of goods	Authorizations for the transport of goods	SEC_12[b]	Number of authorizations year^{-1}	2016	municipality	SIMA
	CO_2 emissions in the transport of goods	SEC_13[a]	Ton CO_2eq inhabitant^{-1} year^{-1}	2013	municipality	REDIAM

Table A2. Descriptive statistics of social-ecological indicators for the entire study area.

Indicator	**ID**	**Unit**	**Mean**	**SD**
Population density	PD_1	People km^{-2}	217.04	762.29
Population dispersion	PD_2	%	5.83	8.36
Population mean age	PD_3	Years	44.11	4.37
Population ageing index	PD_4	Index	204.14	260.48
Rate of natural increase	PD_5	Index	-3.42	6.87
Net migration rate	PD_6	Index	-4.60	17.61
Population over 15 with less than 5 years of school attendance	WB_1	%	16.84	5.82
Unemployment rate	WB_2	%	25.81	5.92
New employment temporary contracts	WB_3	%	96.86	3.99
Mean income	WB_4	€ contributor^{-1} year^{-1}	10669.79	3334.21
Women farm owners	WB_5	%	27.98	8.49
Female unemployment rate	WB_6	% (over unemployed population)	50.15	8.01
Pensioner rate	WB_7	% (over active population)	62.98	44.49
Child dependency ratio	WB_8	%	20.12	5.48
Aged dependency ratio	WB_9	%	32.47	12.09
Mean pension	WB_10	€ pensioner^{-1} month^{-1}	764.69	103.67
Mean pension (non-contributory)	WB_11	€ pensioner^{-1} month^{-1}	373.47	71.60
Turnout in local elections	G_1	%	74.88	10.23
Surplus or deficit in local accounts	G_2	€ inhabitant^{-1} year^{-1}	63.45	202.82
Public expenditure	G_3	€ inhabitant^{-1} year^{-1}	1126.40	490.02
Tax burden	G_4	€ inhabitant^{-1} year^{-1}	465.92	301.52
Agricultural subsidies (CAP payments)	G_5	€ beneficiary^{-1} year^{-1}	6146.88	9756.10
Natural protected area	G_6	%	17.31	31.53
Mean annual EVI	OCD_1	Index	2317.40	451.64

CV annual EVI	OCD_2	Index	0.25	0.09
Mean annual precipitation	WD_1	mm year^{-1}	622.86	199.43
Mean annual potential evapotranspiration	WD_2	mm year^{-1}	824.71	71.81
Moisture index (P/PET)	WD_3	Index	0.76	0.26
Net solar radiation	SEB_1	kW m^{-2} year^{-1}	6002.00	201.62
Mean annual temperature	SEB_2	^{o}C	15.77	1.83
Mean drought standardised index	DR_1	Index	0.21	0.19
Forest fires recurrence	DR_2	Fires year^{-1}	0.07	0.09
Burned surface	DR_3	%	5.72	12.60
Desertification rate (desertified or near to desertification area)	DR_4	%	35.84	33.96
Rainfall maximum torrentiality (from average monthly torrentiality)	DR_5	%	17.51	2.90
Mean annual rain erosivity	DR_6	MJ mm ha^{-1} hour^{-1} year^{-1}	15.86	10.19
Soil erosion rate (area with high annual mean erosion)	DR_7	%	16.28	16.43
Crop production	ESS_1	Ton ha^{-1} year^{-1}	2.17	3.22
Livestock production	ESS_2	Livestock units ha^{-1}	0.18	0.37
Beekeeping	ESS_3	Hives ha^{-1}	0.02	0.07
Fishing	ESS_4	CPUE (Ton kW^{-1} year^{-1})	0.07	0.43
Mean annual protection of vegetation cover against erosion	ESS_5	Index	-3182.70	1288.72
Runoff	ESS_6	Index	78.08	6.03
Optimal suitability area for beekeeping	ESS_7	%	10.44	15.92
Phytocenotic diversity	ESS_8	Index	0.38	0.23
Carbon sequestration by terrestrial ecosystems	ESS_9	Ton ha^{-1}	0.38	0.39
Landscape diversity	ESS_10	Index	2.73	0.15
Landscape naturalness	ESS_11	Index	54.76	27.71
Public use facilities in natural areas	ESS_12	Number of facilities ha^{-1}	0.00	0.04
Habitats of Community Interest (HCI) area	ESS_13	%	36.87	28.90

Mean richness of HCI	ESS_14	Number of HCI	0.72	0.72
Cropland area	ESD_1	%	41.83	28.60
GHG emissions in wastewater treatment	ESD_2	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.09	0.06
CO$_2$ emissions in energy consumption (total)	ESD_3	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.94	1.09
CO$_2$ emissions in energy consumption (agriculture)	ESD_4	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.08	0.33
CO$_2$ emissions in energy consumption (industry)	ESD_5	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.15	0.52
CO$_2$ emissions in energy consumption (service sector)	ESD_6	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.37	6.16
CO$_2$ emissions in energy consumption (residential sector)	ESD_7	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.41	0.46
Artificial surface	HAE_1	%	7.95	11.74
Natural surface	HAE_2	%	50.40	31.15
Cropland productivity	HAE_3	Ton cropland_ha^{-1} year^{-1}	7.73	10.58
Irrigated cropland area	HAE_4	% (of total cropping area)	36.41	32.36
Livestock density	HAE_5	Livestock units grazing_ha^{-1}	4.58	17.98
Area with high agricultural nitrogen input	HAE_6	%	20.10	34.06
GHG emissions in urban waste treatment	HAE_7	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.28	0.12
Night sky quality	HAE_8	Magnit arcseg $^{-2}$	20.71	0.56
Fleet	HAE_9	Vehicles inhabitant^{-1}	0.80	0.39
CO$_2$ emissions by fleet	HAE_10	Ton CO$_2$eq inhabitant^{-1} year^{-1}	1.71	0.81
Total GHG emissions	HAE_11	Ton CO$_2$eq inhabitant^{-1} year^{-1}	5.94	3.52
GHG emissions by crop production	HAE_12	Ton CO$_2$eq inhabitant^{-1} year^{-1}	1.10	1.12
GHG emissions by livestock production	HAE_13	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.93	2.04
CO$_2$ emissions by other fossil fuels	HAE_14	Ton CO$_2$eq inhabitant^{-1} year^{-1}	0.89	1.47
Distance to capital city	HAE_15	Km	64.09	36.88

Employments in agriculture	SEC_1	%	118.44	119.05
New employments in agriculture	SEC_2	%	38.82	25.87
New employments in agriculture + industry	SEC_3	%	43.60	24.97
New employments in service sector	SEC_4	%	43.64	23.58
Organic livestock production	SEC_5	% (of total livestock units)	7.39	18.36
Organic crop production	SEC_6	% (of total agricultural area)	3.25	5.94
Rainfed crop production	SEC_7	% (of total agricultural production)	38.87	33.42
Farms with rural development activities	SEC_8	%	1.31	2.09
Agricultural area under cooperative management	SEC_9	%	1.29	3.91
Average farm area	SEC_10	Ha	31.83	41.03
Young farm owners (< 44)	SEC_11	%	18.99	7.89
Authorizations for the transport of goods	SEC_12	Number of authorizations year^{-1}	0.01	0.01
CO_2 emissions in the transport of goods	SEC_13	Ton CO_2eq inhabitant^{-1} year^{-1}	0.71	0.54

Appendix 2B. Additional results

Tables

Table B1. Description and spatial coverage of social-ecological systems (SESs) of Andalusia.

Category	SES	Description	Area [km^2]	Area share
Natural systems	SES01	**Natural systems (northern mountains):** the largest natural surface, large natural protected area, marginal crop production, large average farm area. The largest suitable area for beekeeping, the highest carbon sequestration rates, low landscape diversity. High unemployment rates. The highest night sky quality, high greenhouse gases emissions.	13375.6	15.3
	SES02	**Natural systems (coastal mountains):** very large natural surface, marginal crop production. High population dispersion, high population mean age. High mean annual precipitations, high soil erosion rate, very high landscape diversity. The highest urban waste production, low territorial connectivity, high transport of goods.	1257.4	1.4
	SES03	**Natural systems (southern mountains):** large natural surface, large natural protected area, marginal crop production, the largest average farm area. The highest mean annual precipitation, the lowest desertification rate, large suitable area for beekeeping. High unemployment rate, low proportion of employments in agriculture. The lowest territorial connectivity.	4058.1	4.6
	SES04	**Natural systems (eastern dryland mountains):** large natural surface, the largest natural protected area, marginal crop production, large average farm area. High net solar radiation, the lowest mean annual temperature, below average mean annual precipitation, high desertification rate. High population mean age.	6873.6	7.8
Mosaic systems	SES05	**Mosaic systems (drylands-eastern)**: high proportion of natural surface (c.a.70%), but reduced proportion of natural protected area, below average crop production (low rainfed crop production), the smallest optimal area for beekeeping. The highest	4765.4	5.4

		population mean age, high population dispersion, high proportion of employments in agriculture, below average mean income and agricultural subsidies. Very low mean annual precipitation, very high desertification rate, below average net solar radiation and mean annual temperature. High rate of transport of goods.		
	SES06	**Mosaic systems (drylands-western)**: the lowest cropland productivity, reduced proportion of natural protected area. Low population dispersion, high proportion of employments and new employments in agriculture, below average mean income and agricultural subsidies. Above average net solar radiation, below average mean annual temperature, high desertification rate. High night sky quality.	7128.2	8.1
	SES07	**Mosaic systems (north-eastern mountains)**: large proportion of natural protected area, very low livestock production. Very low population dispersion, below average unemployment rate, the highest proportion of employments in agriculture and high proportion of new employments in agriculture, the lowest mean income, the lowest agricultural subsidies, below average farm area. Below average net primary productivity seasonality, the lowest net solar radiation and below average annual mean temperature, low desertification rate. The lowest rate of urban waste production, above average night sky quality, very low territorial connectivity, and above average transport of goods.	6918.6	7.9
Agricultural systems	SES08	**Mixed livestock/natural systems (*dehesas* and grasslands plains)**: very high livestock production and high proportion of natural surface. Very low proportion of natural protected area, marginal crop production (mostly rainfed), large average farm area, high agricultural subsidies. The lowest population dispersion, above average population mean age, high unemployment rate. High net primary productivity seasonality, the lowest soil erosion rate. High carbon sequestration	4267.5	4.9

	rate, low landscape diversity. High night sky quality, the highest rate of greenhouse gases emission. Low territorial connectivity.		
SES09	**Mixed livestock/cropping systems (mountains)**: the highest livestock production and reduced proportion of natural surface. Very low proportion of natural protected area, on average crop production (mostly rainfed), small average farm area, below average agricultural subsidies. Below average carbon sequestration rate, high landscape diversity. Low territorial connectivity.	5535.2	6.3
SES10	**Extensive cropping systems (olive grove monocultures in the upper Guadalquivir plain):** low cropland productivity, the smallest natural surface and reduced proportion of natural protected area. Below average agricultural subsidies and farm area. The lowest net primary productivity seasonality, high soil erosion rate and very low carbon sequestration rate. High proportion of employments and new employments in agriculture, below average unemployment rate.	5684.3	6.5
SES11	**Extensive cropping systems (middle-low Guadalquivir plain):** very high crop production, the lowest landscape diversity, reduced natural surface and natural protected area. The highest net primary productivity seasonality (dominant seasonal crops), above average mean annual temperature and low carbon sequestration rate. Below average night sky quality, high territorial connectivity. Below average population mean age, above average mean income and low proportion of employments in agriculture.	15312.6	17.5
SES12	**Cropping systems in valleys of southern coastal mountains:** high crop production and cropland productivity, below average natural surface area and the smallest proportion of natural protected area. The smallest average farm area. Below average net solar radiation, above average mean annual temperature. The highest soil erosion rate, very high desertification rate and very low carbon sequestration rate. High landscape diversity index. The	1489.5	1.7

		greatest population dispersion, high urban waste production, below average night sky quality, high territorial connectivity.		
	SES13	**Moderately intensified cropping systems (western lowlands):** very high cropland productivity, high agricultural subsidies. Below average population mean age, below average proportion of employments in agriculture. Very high net solar radiation and the highest mean annual temperature, very low soil erosion rates. Remaining natural area c.a. 62%, large suitable area for beekeeping, high carbon sequestration rate. High territorial connectivity.	4789.3	5.5
	SES14	**Intensified cropping systems (eastern drylands):** the highest crop production, cropland productivity, agricultural subsidies, and transport of goods. Below average farm area. Remaining natural area c.a. 62%, but reduced proportion of natural protected area. The lowest rainfed crop production. The lowest mean annual precipitation, above average mean annual temperature, the highest desertification rate and the lowest carbon sequestration rate. Below average population mean age, above average mean income, and the lowest unemployment rate.	3368.8	3.8
Urban systems	SES15	**Urban systems:** the highest population density, very low population dispersion, the lowest population mean age, the highest mean income. Low proportion of natural surface, below average supply of provisioning (livestock production) and regulating (carbon sequestration, optimal area for beekeeping) ecosystem services, the lowest proportion of employments and new employments in agriculture. Low urban waste production rate, the lowest rate of greenhouse gases emissions and of CO_2 emissions in goods transport. The highest territorial connectivity. The lowest night sky quality.	2785.9	3.2

Figures

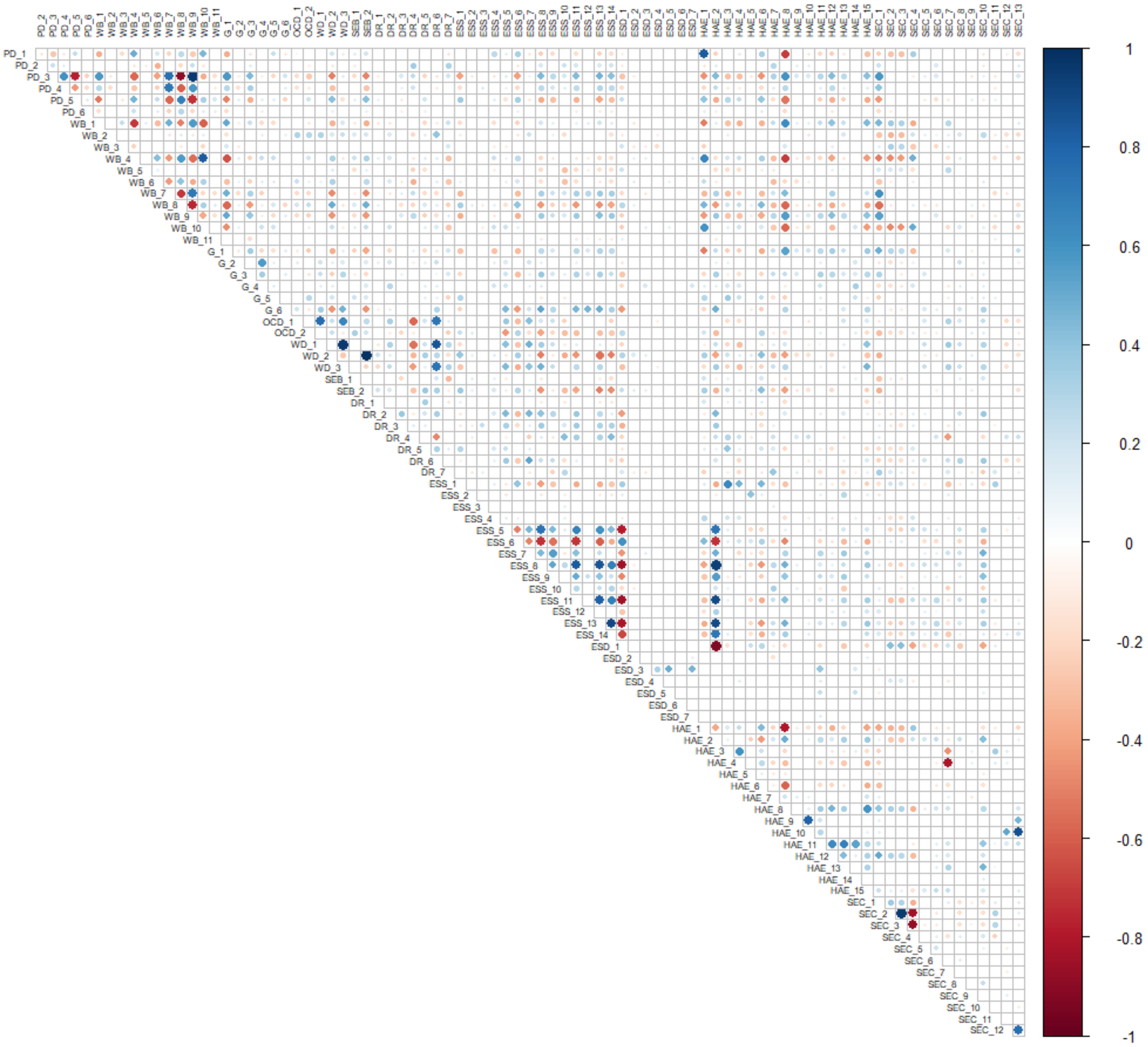


Fig. B1. Pearson’s correlation matrix of the 86 indicators used in the analysis. Blue and red dots indicate positive and negative correlation, respectively. Dots size and colour intensity reflect the magnitude of correlation. We identified several groups of correlated indicators. In the social system component, we found significant correlations among indicators referring to population ageing, natural population growth and population dependency. We also found correlations among population density, well-being related indicators (e.g., mean income), and human influence indicators (e.g., artificial surface and night sky quality). In the ecological system component, we found correlations between indicators related to organic carbon dynamics (e.g., net primary productivity), water dynamics (e.g., mean annual precipitation, moisture index), and disturbance regime (e.g., mean annual rain erosivity). Finally, in the interaction component, the main correlations were found among ecosystem service indicators (e.g., protection of vegetation cover against erosion, pollination, phytocenotic diversity, landscape naturalness, Habitats of Community Interest area and richness). In turn, these ecosystem service indicators were positively correlated with natural surface area and negatively correlated with cropland area indicators. Please, see in Appendix A, Table A.1 the least relevant indicators that were discarded from these highly correlated groups.

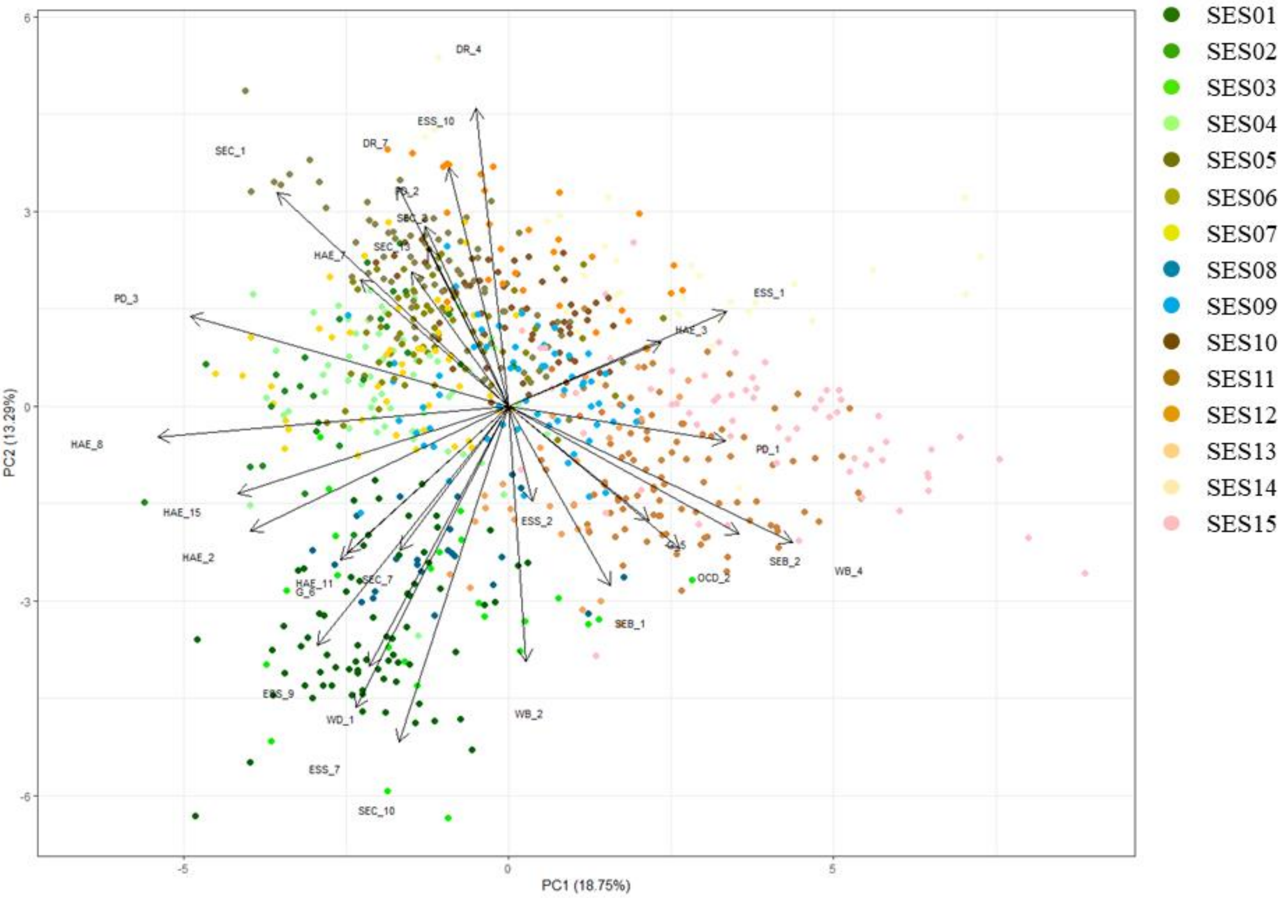


Fig. B2. Principal component analysis obtained for the 29 selected indicators. The two first components of the PCA explain the 32.04% of the variation across municipalities (dots). Dots colour indicates the SES cluster. The length of the arrows indicates the contribution of each indicator to the PCA space. **ESS_1**: crop production; **HAE_3**: cropland productivity; **PD_1**: population density; **WB_4**: mean income; **SEB_2**: mean annual temperature; **G_5**: agricultural subsidies; **OCD_2**: enhanced vegetation index coefficient of variation; **SEB_1**: net solar radiation; **ESS_2**: livestock production; **WB_2**: unemployment rate; **SEC_10**: average farm area; **ESS_7**: optimal suitability area for beekeeping; **WD_1**: mean annual precipitation; **SEC_7**: rainfed crop production; **ESS_9**: carbon sequestration by terrestrial ecosystems; **G_6**: natural protected area; **HAE_11**: total greenhouse gas emissions; **HAE_2**: natural surface; **HAE_15**: distance to capital city; **HAE_8**: night sky quality; **PD_3**: population mean age; **HAE_7**: greenhouse gas emissions in urban waste treatment; **SEC_1**: employments in agriculture; **SEC_13**: carbon dioxide emissions in goods transport; **SEC_2**: new employments in agriculture; **DR_7**: soil erosion rate; **PD_2**: population dispersion; **ESS_10**: landscape diversity; **DR_4**: desertification rate.

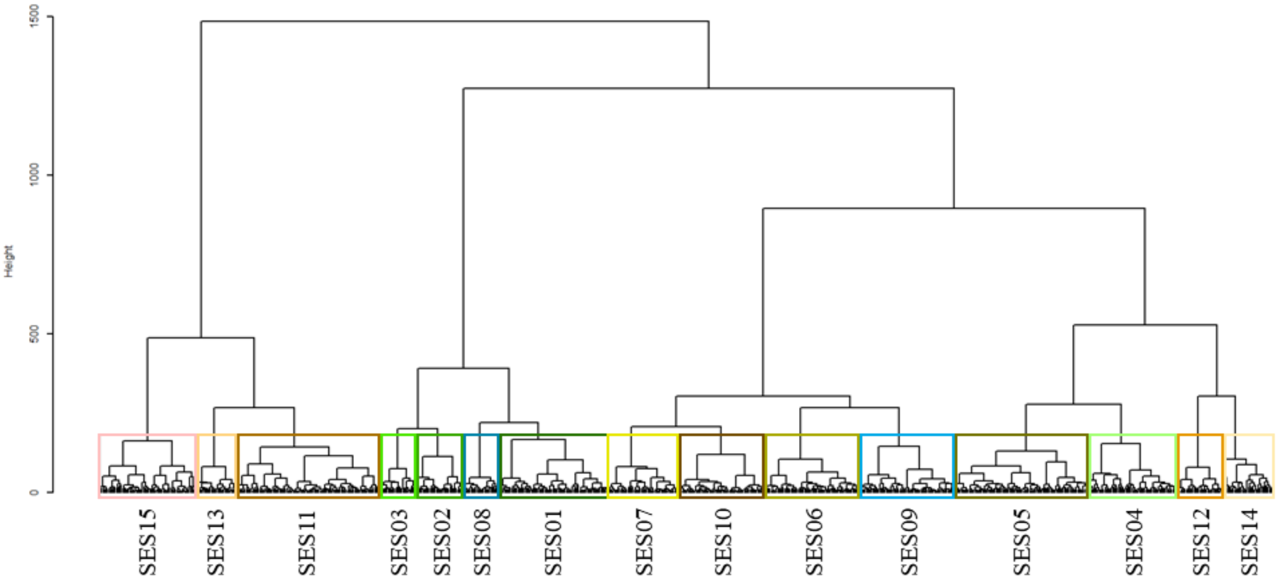


Fig. B3. Cluster dendrogram of the identified SESs.

Apéndices del resultado 2.3

Appendix 3A. Indicators

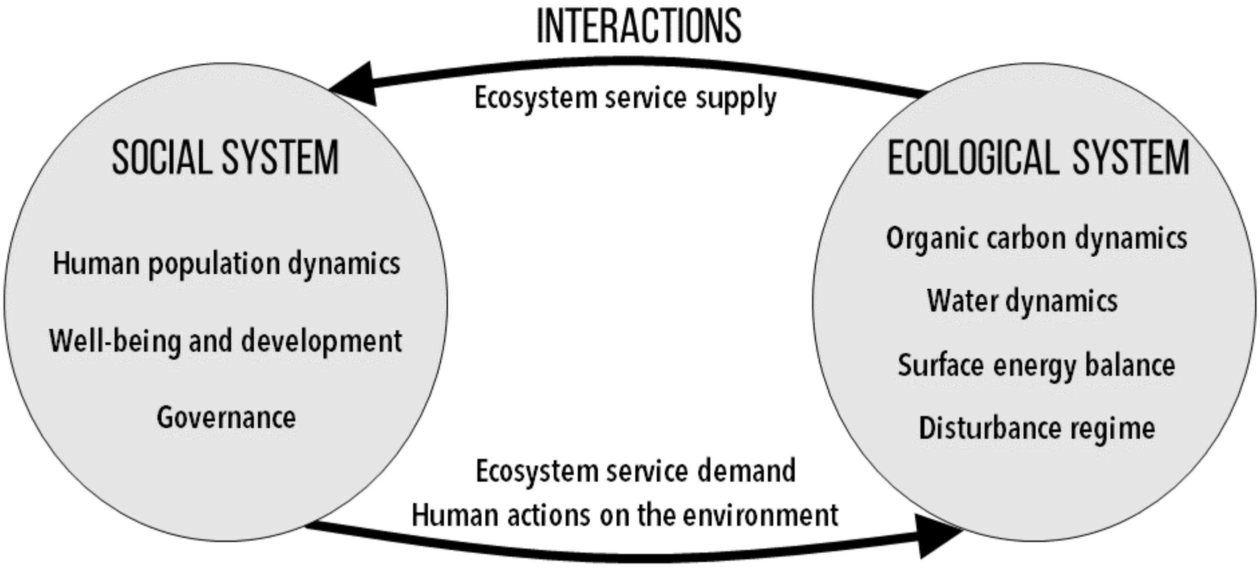


Fig. A1. Conceptual framework of the social-ecological system used to structure the database and to guide the characterization of typical social-ecological systems and social-ecological changes. The three main components of the socio-ecological system are shown in capital letters: the social system, 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 A1. Indicators used for the detection and mapping of typical social-ecological systems and social-ecological changes.

Variable	**Indicator**	**Unit**	**Time period**		**Resolution**	**Source**
			T_o	T_1		
Social system						
Human population dynamics						
Population density	Population density	People km^{-2}	1999	2016	municipality	SIMA
Population distribution	Population dispersion	%	1999	2016	municipality	SIMA
Population ageing	Population mean age	years	2001	2016	municipality	SIMA
Well-being and development						
Employment	Unemployment rate	%	2001	2016	municipality	SIMA
Economic level	Mean income	€ contributor^{-1} year^{-1}	1999	2015	municipality	SIMA
Governance						
Participation	Turnout in local elections	%	1999	2015	municipality	SIMA
Internal capacity of the government	Public expenditure	€ inhabitant^{-1} year^{-1}	1999	2016	municipality	SIMA
Ecological System						
Organic carbon dynamics						
Net Primary Productivity (NPP)	Mean annual EVI	Index	2001-2009	2010-2016	raster (230 m)	NASA-MODIS
Net Primary Productivity seasonality (NPP seasonality)	CV annual EVI	Index	2001-2009	2010-2016	raster (230 m)	NASA-MODIS

Water dynamics						
Precipitation	Mean annual precipitation	mm year^{-1}	1990-1999	2007-2016	raster (100 m)	REDIAM
Surface energy balance						
Air temperature	Mean annual temperature	°C	1990-1999	2007-2016	raster (100 m)	REDIAM
Disturbance regime						
Drought occurrence	Mean drought standardized index	Index	1990-1999	2007-2016	raster (1000 m)	REDIAM
Rainfall torrentiality	Rainfall mean torrentiality	%	1990-1999	2007-2016	raster (1000 m)	REDIAM
Interactions						
Ecosystem service supply						
Cultivated crops (P)	Crop production	Ton ha^{-1} year^{-1}	1999	2015	municipality	IECA, SIMA
Reared animals and their outputs (P)	Livestock production (GHG emissions by livestock)	Ton CO_2eq ha^{-1} year^{-1}	2000	2013	municipality	REDIAM
Global climate regulation by reduction of greenhouse gas concentrations (R)	Carbon sequestration by terrestrial ecosystems	Ton ha^{-1}	2000	2013	municipality	REDIAM
Physical and experiential interactions (C)	Landscape diversity index	Index	1999	2011	shape (polygon)	REDIAM
Ecosystem service demand						

Appropriation of land for agriculture	Cropland area	%	1999	2015	municipality	SIMA
Human actions on the environment						
Land use/ land cover	Natural surface	%	1999	2013	municipality	SIMA
	Artificial surface	%	1999	2013	municipality	SIMA
Land use intensity	Cropland productivity	Ton cropland_ha^{-1} year^{-1}	1999	2015	municipality	IECA, SIMA
	Irrigated cropland area	% (of total cropland area)	1999	2015	municipality	SIMA
Traditional/ Organic agriculture	Rainfed crop production	% (of total cropland production)	1999	2015	municipality	IECA, SIMA
Transport of goods	CO_2 emissions in the transport of goods	Ton CO_2eq ha^{-1} year^{-1}	2000	2013	municipality	REDIAM
Anthropogenic greenhouse gases emission	Total GHG emissions	Ton CO_2eq ha^{-1} year^{-1}	2000	2013	municipality	REDIAM
Soil erosion	Area with high annual mean erosion	%	1999	2015	municipality	SIMA

Indicator sources, processing, and aggregation

We used free public regional databases to derive the indicators: the Environmental Information Network of Andalusia (REDIAM), the Multi-Territorial Information System of Andalusia (SIMA) and the Agrarian Census, these two latter belonging to the Institute of Statistics and Cartography of Andalusia (IECA) database (Table A.1).

Within the social system component, we used seven indicators to characterize three dimensions. The *Human population dynamics* dimension was explained by population density, population distribution (percentage of disseminated population) and population ageing. *Wellbeing and development* of the population was inferred from unemployment rate and the income level. The *governance* dimension was introduced through the participation of the population in local elections and the internal capacity of the government (public expenditure per inhabitant).

For the ecological system component, we used six indicators that explained four dimensions. Given the interannual variability of the selected indicators, we calculated a 10-year average to obtain a more representative value for t_0 and t_1. Thus, t_0 summarized the period 1990-1999, and t_1 the period 2007-2016. To characterize *organic carbon dynamics* dimension, we used two key descriptors of ecosystem functioning: the net primary productivity (NPP) and NPP seasonality (McNaughton et al., 1989). These were derived from the annual mean and the annual coefficient of variation, respectively, of the Enhanced Vegetation Index (EVI) from Moderate-Resolution Imaging Spectrometer (NASA-MODIS) satellite images (MOD13Q1 product). Due to the narrower temporal availability of this product, we calculated t_0 for the period 2001-2009 (instead of 1990-1999) and t_1 for the period 2010-2016 (instead of 2007-2016). For *water dynamics* and *surface energy balance* dimensions, we used mean annual precipitation and mean annual temperature, respectively. Finally, to characterize the *disturbance regime* we introduced two common disturbances of the Mediterranean climate whose frequency and intensity are tending to increase due to climate change: drought occurrence and rainfall torrentiality.

Regarding the interactions between humans and nature, we used 13 indicators to introduce three additional dimensions. From the ecological to the social system, we characterized *ecosystem service supply* dimension with four representative services according to the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2013): crop production and livestock production (provisioning services), carbon sequestration by terrestrial ecosystems (regulating), and landscape diversity (cultural). From the social to the ecological system we incorporated the *ecosystem service demand* dimension from the appropriation of land for agriculture. In addition, we characterized *human actions on environment* dimension through indicators representative of: land use/land cover (natural surface, artificial surface), land use intensity (cropland productivity, irrigated cropland area), traditional agricultural practices (rainfed crop production), transport of goods, greenhouse gas emissions, and soil erosion.

References

Haines-Young, R., Potschin, M., 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012.

McNaughton, S.J., Oesterheld, M., Frank, D.A., Williams, K.J., 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. Nature 341, 142. https://doi.org/10.1038/341142a0

Table A2. Descriptive statistics of social-ecological indicators for the entire study area.

Indicator	**Unit**	**2016**		**∆1999-2016**	
		Mean	SD	Mean	SD
Population density	People km^{-2}	452.1	1,134.7	65.1	258.1
Population dispersion	%	6.4	6.4	1.9	2.8
Population mean age	years	43.4	3.5	3.1	0.5
Unemployment rate	%	26.2	3.4	-0.4	7.1
Mean income	€ contributor^{-1} year^{-1}	1,1414.8	3,146.1	2,627.1	864.6
Turnout in local elections	%	72.9	8.1	-1.3	4.8
Public money expending	€ inhabitant^{-1} year^{-1}	1,072.0	344.5	521.1	235.4
NPP (mean annual EVI)	Index	0.2	0.0	0.0	0.0
NPP season. (CV annual EVI)	Index	0.3	0.1	0.0	0.0
Mean annual precipitation	mm year^{-1}	599.9	216.0	166.7	112.8
Mean annual temperature	ºC	17.0	1.1	0.4	0.3
Mean drought index	Index	0.3	0.1	0.5	0.4
Rainfall mean torrentiality	%	8.9	0.5	0.9	1.1
Crop production	Ton ha^{-1} year^{-1}	2,752.0	3,582.6	1,019.3	1,648.0
Livestock production	Ton CO$_2$eq ha^{-1} year^{-1}	0.2	0.2	0.0	0.0
Carbon sequestration	Ton ha^{-1}	0.3	0.3	0.0	0.0
Landscape diversity index	Index	1.9	0.3	0.2	0.1
Cropland area	%	33.0	24.2	-3.0	3.5
Natural surface	%	49.0	26.5	5.7	6.4
Artificial surface	%	11.8	15.7	5.3	4.4
Cropland productivity	Ton cropland_ha^{-1} year^{-1}	10,998.8	14,874.7	4,279.3	6,983.1
Irrigated cropland area	% (of total cropland area)	38.3	27.0	5.0	8.8
Rainfed crop production	% (of total cropland production)	39.0	27.8	-2.6	9.2
Transport of goods	Ton CO$_2$eq ha^{-1} year^{-1}	1.5	2.6	-1.0	2.1
Total GHG emissions	Ton CO$_2$eq ha^{-1} year^{-1}	14.7	32.0	-4.0	15.4
Soil erosion	%	0.1	0.1	0.0	0.0

Table A3. Selected proxies from the main database to assess biophysical connectedness dimensions, based on Dorninger et al. (2017) framework.

Dimension	**Description**	**Proxies**
Intraregional connectedness	Baseline to compare SESs according to human appropriation of net primary production (HANPP)	Net Primary Productivity (NPP) (mean annual EVI) Cropland area (% of the municipality area) Crop production (Ton harvested crops · municipality_ha^{-1}) Livestock production (GHG emissions by livestock: Ton CO_2eq · ha^{-1} · year^{-1})
Biospheric disconnectedness	Use of material inputs (agrochemicals, fossil fuels, water, machinery) to increase cropland productivity	Cropland productivity (Ton harvested crops · cropland_ha^{-1})
Spatial disconnectedness	Biomass-based commodities imported to and exported from a region, plus minerals imported for land use related activities	Transport of goods (Ton CO_2eq · ha^{-1} · year^{-1})

Appendix 3B. Additional results

TABLES

Table B1. Description and spatial coverage of typical social-ecological systems (SESs).

SES	Description	Area [km^2]	Area share
SES01	**Natural systems (southern mountains)**: very large natural surface; low population density, high population ageing, high turnout in local elections and high public expenditure; marginal crop production (mostly rainfed), high carbon sequestration rate and landscape diversity; very high mean precipitation and rainfall torrentiality, high net primary productivity (NPP), below average mean temperatures.	1,033	1.2%
SES02	**Natural systems (western mountains)**: large natural surface; low population density, high unemployment rate; marginal crop production (mostly rainfed), high carbon sequestration rate; high mean precipitation and NPP.	12,620	14.4%
SES03	**Natural systems (eastern mountains)**: large natural surface; low population density, high population ageing and high turnout in local elections; below average mean precipitation, mean temperature, and NPP; low crop production, above average carbon sequestration rate and landscape diversity.	11,753	13.4%
SES04	**Mosaic systems (inland mountains)**: average cropland productivity and crop production; below average mean temperature and NPP seasonality; below average mean income.	17,222	19.7%
SES05	**Mosaic systems (coastal mountain)**: average cropland productivity and crop production; high population dispersion and high population ageing, below average mean income; below average NPP seasonality; high landscape diversity, large eroded surface.	1,291	1.5%
SES06	**Mosaic systems (western lowlands)**: average crop production, balance between irrigated and rainfed crops; above average mean temperatures; above average carbon sequestration rate and landscape diversity.	7,329	8.4%
SES07	**Mixed livestock/cropping systems (*dehesas* and grasslands plains)**: very high livestock production, dominance of rainfed crops, large natural surface area; high carbon sequestration rate, low landscape diversity; high NPP seasonality; above average population ageing, very high unemployment rate and turnout in local elections.	4,958	5.7%
SES08	**Mixed livestock/cropping systems (mountains)**: high livestock production, above average cropland area, dominance of rainfed crops, large eroded area; above average NPP seasonality; high unemployment rate and turnout in local elections, below average mean income.	2,791	3.2%

SES09	**Extensive cropping systems (olive grove monocultures in the upper Guadalquivir plain)**: very large cropland area, high rainfed crop production, very low landscape diversity, below average carbon sequestration rate; below average unemployment rate.	7,056	8.1%
SES10	**Extensive cropping systems (arable seasonal crops in the middle Guadalquivir plain)**: large cropland area, high rainfed crop production; above average mean temperatures, very high NPP seasonality; low landscape diversity, below average carbon sequestration rate.	9,470	10.8%
SES11	**Extensive cropping systems (lowlands - marshes and river valleys)**: large cropland area, dominance of irrigated crops, high crop production; above average NPP and NPP seasonality.	5,756	6.6%
SES12	**Intensified cropping systems (drylands-eastern)**: below average cropland area, high cropland productivity, dominance of irrigated crops; large natural surface area, low NPP, very high drought index; below average carbon sequestration rate.	2,597	3.0%
SES13	**Intensified cropping systems (drylands-western)**: very high cropland productivity and crop production, dominance of irrigated crops; high drought index and rainfall torrentiality, below average NPP; below average carbon sequestration rate; below average population ageing and unemployment rate.	1,484	1.7%
SES14	**Peri-urban systems**: large artificial surface, high population density, low population ageing, high mean income, low turnout in local elections; average cropland productivity and crop production; high greenhouse gas emissions.	1,827	2.1%
SES15	**Urban systems**: very large artificial surface, very high population density, below average population ageing, high mean income, low turnout in local elections; marginal cropland area, low carbon sequestration rate, very high greenhouse gas emissions.	424	0.5%
		87,610	**100%**

Table B2. Description and spatial coverage of typical social-ecological changes (SECHs).

SECH	Description	Area [km^2]	Area share
SECH01	**Cropland expansion & intensification (south-eastern drylands)**: great cropland intensification; increase in the drought index; rise in unemployment.	2,795	3.2%
SECH02	**Cropland intensification & peri-urbanization (coastal mountains)**: expansion of irrigated crops over rainfed traditional croplands, increase in eroded surface, the greatest increase in natural surface area and landscape diversity index; increase in NPP; the greatest rise in population dispersion and population ageing, decrease in unemployment rate.	867	1.0%
SECH03	**Cropland intensification (upper Guadalquivir basin)**: increase in irrigated cropland surface and the greatest rise in carbon sequestration rate; decrease in the drought index; increase in eroded surface.	16,561	18.9%
SECH04	**Cropland expansion & peri-urbanization (low Guadalquivir basin)**: increase in cropland area and crop production (mostly rainfed crops), great increase in artificial surface; the lowest increase in population mean age, above average increase in mean income, and the highest decrease in turnout in local elections.	8,384	9.6%
SECH05	**Stockbreeding expansion (marginal lands)**: increase in livestock activity, decrease in cropland area; above average ageing and decrease in unemployment rate; the greatest increase in mean temperature.	11,654	13.3%
SECH06	**Declining crop and livestock production (mountains)**: decrease in livestock and crop production; above average population ageing, increase in unemployment rate and turnout in local elections; the highest increase in mean precipitation and rainfall torrentiality, the highest decrease in NPP seasonality.	1,207	1.4%
SECH07	**Cropland deintensification (eastern-western mosaics)**: the greatest reduction in irrigated crops area; decrease in average temperature.	10,996	12.6%
SECH08	**Increasing aridity (eastern drylands)**: increase in the drought index; the greatest NPP decline and the greatest increase in NPP seasonality.	3,148	3.6%
SECH09	**Increasing public expenditure**: the highest increase in public expenditure by local administration, below average increase in population mean age.	6,691	7.6%
SECH10	**Urbanization**: the highest increase in artificial surface, population density, and mean income; the lowest increase in population mean age and in the expend of public expenditure, decrease in the turnout in local elections; the highest increase in greenhouse gas emissions.	830	0.9%
SECH11	**Counter-urbanization**: the highest population density decrease; the highest reduction in greenhouse gas emissions (total) and in those caused by the transport of goods.	307	0.3%
SECH12	**Stability**: no substantial changes for the indicators.	24,168	27.6%
		87,610	**100%**

Table B3. Characteristics of each identified typical social-ecological system (SES). The larger the deviance from the study area average, the higher the impact of a given indicator on the respective SES. The + and - signs indicate whether an indicator is above or below the study area average; the absence of any sign indicates no substantial deviance from the study area average. We used the following thresholds: + from ≥ 0.5 up to 1 SD, ++ from ≥ 1 up to 2 SD, and +++ ≥ 2 SD.

COMPONENT/*Dimension*/Indicator		Social-ecological systems (2016)														
		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
SOCIAL SYSTEM																
Human population dynamics																
	Population density															+++
	Population dispersion					+++		-		-	-	-			-	-
	Population mean age	++		++		++	-	++			-	-		--	--	-
Well-being and development																
	Unemployment rate		++	-	-	+		++	+	--	+	+	-	--		
	Mean income	-		-	-	--			-	-					+++	+++
Governance																
	Turnout in local elections	++		+	+	+		++	+	+	-	-		-	--	--
	Public expenditure	+++				++	-				-	-	-		-	
ECOLOGICAL SYSTEM																
Organic carbon dynamics																
	NPP (mean annual EVI)	++	++	--			+	+				+	--	--		-
	NPP season. (CV annual EVI)	-	-		--	--		++	+	-	+++	+				-
Water dynamics																

	Mean annual precipitation	+++	++	-									--	--		
Surface energy balance																
	Mean annual temperature	--		---	--	-	++	-			++	+	+	+		+
Disturbance regime																
	Mean drought index		-	+				-			-	-	+++	+	-	
	Rainfall mean torrentiality	++		--		--	-	-	-	+		+	--	++		
INTERACTIONS																
Ecosystem service supply																
	Crop production	-	-	-				-				++		+++		-
	Livestock production			-	-	-		+++	++					-		
	Carbon sequestration	++	+++	+		-	+	++		-	-		-	-	-	--
	Landscape diversity index	+		+		+	+	--		---	--		+		+	
Ecosystem service demand																
	Cropland area	-	--	-					+	+++	++	++	-			--
Human actions on the environment																
	Natural surface	++	++	+				+	-	--	--	-	+		-	-
	Artificial surface	-	-	-	-	-		-							++	+++
	Cropland productivity	-							-		-		+	+++		
	Irrigated cropland area	--	-			-		--	--		-	++	++	++		+
	Rainfed crop production	+	+	-			-	++	++	+	+	--	--	--		-
	Transport of goods	-	-	-				-							+	+++

Total GHG emissions														+	+++
Soil erosion	++	-	-	+	+++	-	-	++		-	-	-			-

Table B4. Cross-tabulation of the spatial overlap [km²] between typical social-ecological systems (SESs) and social-ecological changes (SECHs).

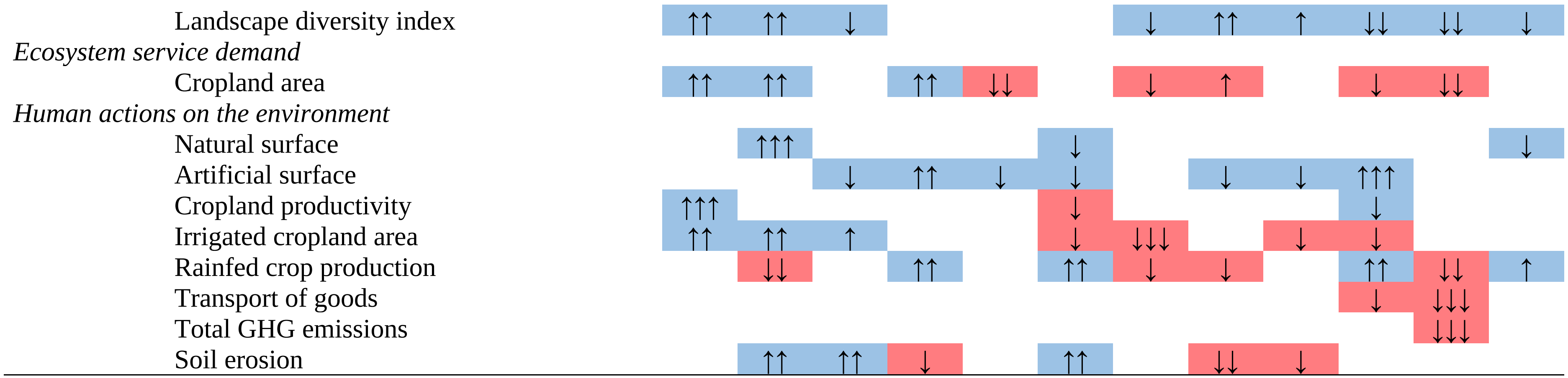
	SES01	SES02	SES03	SES04	SES05	SES06	SES07	SES08	SES09	SES10	SES11	SES12	SES13	SES14	SES15
SECH01	0.0	0.0	158.0	67.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,076.0	1,406.1	87.7	0.0
SECH02	0.0	0.0	0.0	133.4	309.3	0.0	0.0	201.1	0.0	0.0	223.3	0.0	0.0	0.0	0.0
SECH03	155.8	548.2	402.1	8,782.7	0.0	72.1	0.0	310.5	4,963.5	168.4	1,072.5	0.0	0.0	85.0	0.0
SECH04	0.0	0.0	0.0	0.0	0.0	518.7	0.0	22.3	52.1	4,896.1	2,639.1	0.0	0.0	255.9	0.0
SECH05	0.0	287.1	3,365.6	2,071.5	180.9	502.8	3,249.5	1,340.4	158.2	0.0	497.9	0.0	0.0	0.0	0.0
SECH06	351.4	828.6	0.0	0.0	27.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SECH07	43.9	1,776.0	1,502.6	1,960.0	194.1	2,751.5	0.0	224.2	1,245.5	0.0	769.1	412.1	0.0	0.0	117.2
SECH08	0.0	0.0	2,105.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,042.8	0.0	0.0	0.0
SECH09	481.9	458.5	3,170.6	458.0	579.3	296.0	0.0	608.2	0.0	0.0	0.0	66.0	28.5	544.3	0.0
SECH10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	354.6	168.8	0.0	0.0	158.4	148.6
SECH11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.7	99.7	157.8
SECH12	0.0	8,721.3	1,048.9	3,748.3	0.0	3,188.0	1,708.2	84.0	637.1	4,050.9	385.6	0.0	0.0	596.1	0.0

Table B5. Particular co-occurrences between typical social-ecological changes (SECHs) and social-ecological systems (SESs) associated to potential sustainability challenges identified in the study area (see Fig. 5 in the paper).

Sustainability challenge	**Co-occurrence of SESs and SECHs**
A	SECH01 on SES12 and SES13
B	SECH08 on SES12
C	SECH02 on SES05
D	SECH10 on SES10
E	SECH04 on SES10 and SES11
F	SECH11 on SES14 and SES15
G	SECH08 on SES03
H	SECH06 on SES01 and SES02

FIGURES

	Social-ecological changes (1999-2016)											
	01	02	03	04	05	06	07	08	09	10	11	12
SOCIAL SYSTEM												
Human population dynamics												
Population density										🟦 ↑↑↑	🟥 ↓↓	
Population dispersion	🟦 ↓	🟦 ↑↑↑	🟦 ↓							🟥 ↓		🟦 ↓
Population mean age	🟦 ↓↓	🟦 ↑↑		🟦 ↓↓	🟦 ↑↑	🟦 ↑↑		🟦 ↑	🟦 ↓	🟦 ↓		
Well-being and development												
Unemployment rate	🟦 ↑↑	🟥 ↓↓	🟥 ↓		🟥 ↓↓	🟦 ↑↑	🟥 ↓↓	🟦 ↑		🟦 ↑↑	🟦 ↑	
Mean income	🟦 ↓	🟦 ↓	🟦 ↓	🟦 ↑			🟦 ↓		🟦 ↓	🟦 ↑↑↑	🟦 ↑	
Governance												
Turnout in local elections	🟥 ↓			🟥 ↓↓	🟦 ↑	🟦 ↑↑		🟦 ↑↑	🟦 ↑	🟥 ↓↓	🟦 ↑↑	🟥 ↓
Public expenditure	🟦 ↓	🟦 ↑↑	🟦 ↓	🟦 ↓		🟦 ↓↓			🟦 ↑↑↑	🟦 ↓↓	🟦 ↑	
ECOLOGICAL SYSTEM												
Organic carbon dynamics												
NPP (mean annual EVI)		🟦 ↑↑	🟦 ↑				🟦 ↑	🟥 ↓↓↓	🟥 ↓	🟦 ↑	🟦 ↑	🟥 ↓↓
NPP season. (CV annual EVI)	🟦 ↑				🟦 ↑	🟥 ↓↓↓		🟦 ↑	🟥 ↑	🟥 ↓		
Water dynamics												
Mean annual precipitation	🟦 ↓					🟦 ↑↑↑		🟥 ↓↓				
Surface energy balance												
Mean annual temperature	🟦 ↓↓	🟦 ↑			🟦 ↑↑	🟦 ↓	🟥 ↓↓	🟦 ↓↓		🟦 ↑↑	🟦 ↑	
Disturbance regime												
Mean drought index	🟦 ↑↑		🟥 ↓↓	🟥 ↓		🟥 ↓↓		🟦 ↑↑	🟥 ↑			
Rainfall mean torrentiality	🟦 ↓		🟦 ↑			🟦 ↑↑		🟥 ↓↓↓	🟦 ↓			
INTERACTIONS												
Ecosystem service supply												
Crop production	🟦 ↑↑↑			🟦 ↑		🟥 ↓			🟦 ↓	🟦 ↓		🟦 ↓
Livestock production					🟦 ↑↑	🟥 ↓↓↓						
Carbon sequestration	🟦 ↓	🟦 ↓	🟦 ↑↑↑	🟦 ↑↑	🟦 ↑	🟦 ↓		🟦 ↓	🟦 ↓		🟦 ↓	



Landscape diversity index	🟦 ↑↑	🟦 ↑↑	🟦 ↓				🟦 ↓	🟦 ↑↑	🟦 ↑	🟦 ↓↓	🟦 ↓↓	🟦 ↓
Ecosystem service demand												
Cropland area	🟦 ↑↑	🟦 ↑↑		🟦 ↑↑	🟥 ↓↓		🟥 ↓	🟥 ↑		🟥 ↓	🟥 ↓↓	
Human actions on the environment												
Natural surface		🟦 ↑↑↑				🟦 ↓						🟦 ↓
Artificial surface			🟦 ↓	🟦 ↑↑	🟦 ↓	🟦 ↓		🟦 ↓	🟦 ↓	🟦 ↑↑↑		
Cropland productivity	🟦 ↑↑↑					🟥 ↓				🟦 ↓		
Irrigated cropland area	🟦 ↑↑	🟦 ↑↑	🟦 ↑			🟥 ↓	🟥 ↓↓↓		🟥 ↓	🟥 ↓		
Rainfed crop production		🟥 ↓↓		🟦 ↑↑		🟦 ↑↑	🟥 ↓	🟥 ↓		🟦 ↑↑	🟥 ↓↓	🟦 ↑
Transport of goods										🟥 ↓	🟥 ↓↓↓	
Total GHG emissions											🟥 ↓↓↓	
Soil erosion		🟦 ↑↑	🟦 ↑↑	🟥 ↓		🟦 ↑↑		🟥 ↓↓	🟥 ↓			

Fig. B1. Indicator-specific magnitude of change per typical social-ecological change (SECH). The larger the deviance from the study area average, the higher the change of a given indicator (↑ and ↓ indicate values above or below the study area average). Blue and red colours indicate the general trend (increase or decrease, respectively). Hence, indicator values can increase (blue) above average (↑) or below average (↓), or decrease (red) more than average (↓) or less than average (↑). Thresholds used: ↑ = 0.5 - 1 SD, ↑↑ 1 - 2 SD, and ↑↑↑ ≥ 2 SD.

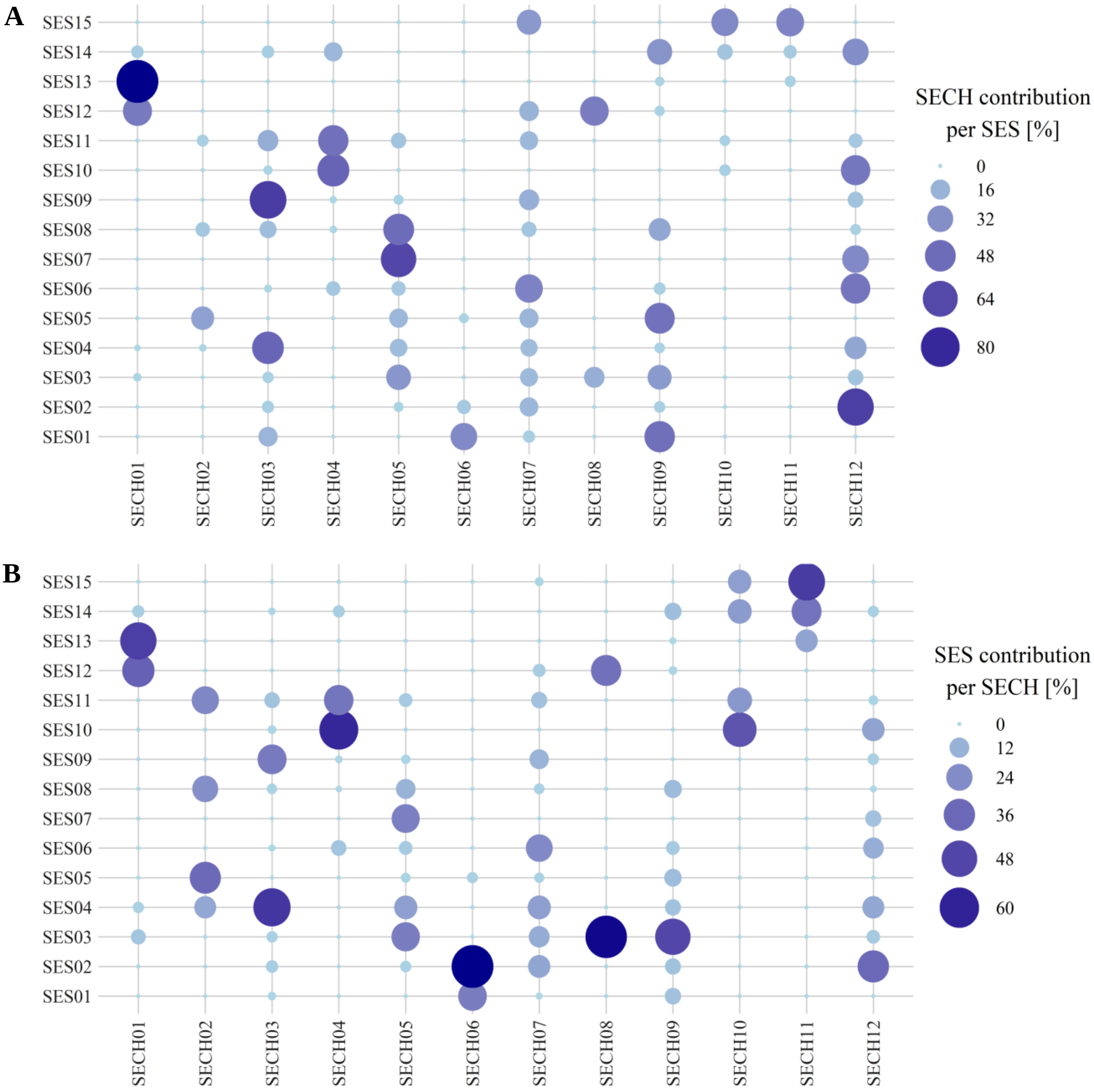


Fig. B2. Spatial coverage (%) of each SECH per SES (A) and of each SES per SECH (A). Rows in A and columns in B sum up to 100% spatial extent. Circle sizes and colour gradient depict the magnitude of co-occurrence.

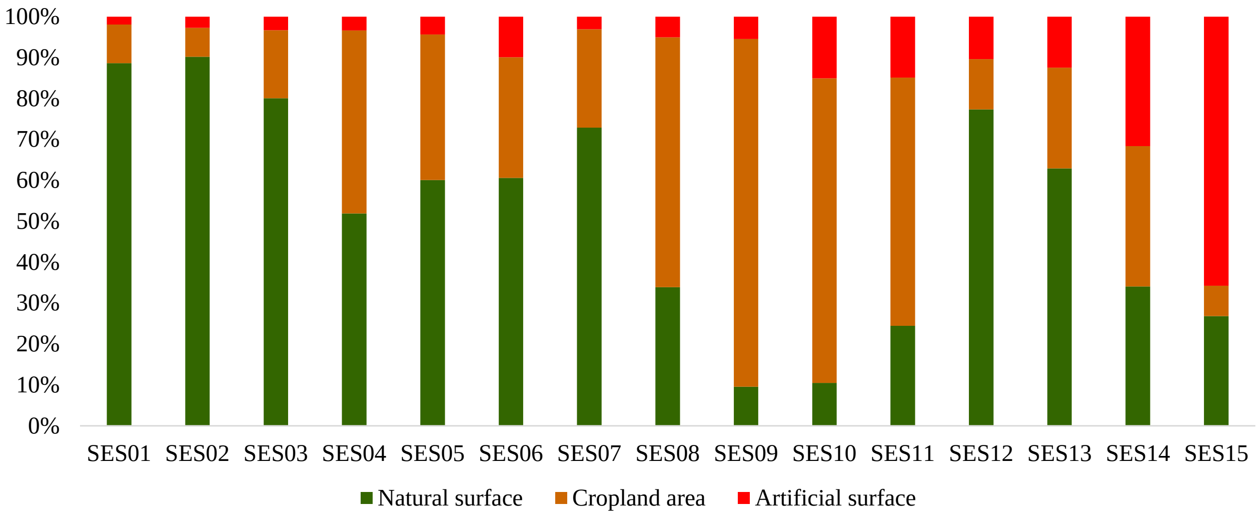


Fig. B3. Land area (%) covered by natural, cropland, and artificial surfaces in each typical social-ecological system (SES). The dominance of natural and/or cropland indicates a high dependence on local natural capital (*green-loop* SESs), whereas the dominance of artificial surface indicates a low dependence on local natural capital (*red-loop* SESs). A balance among both indicates an intermediate dependence on local natural capital (*transition* SESs).

PUBLICACIONES DERIVADAS DE ESTA TESIS

Publicaciones principales

1. Pacheco-Romero, M., Alcaraz-Segura, D., Vallejos, M., and Cabello, J. (2020). An expert-based reference list of variables for characterizing and monitoring social-ecological systems. *Ecology and Society*, 25(3):1. https://doi.org/10.5751/ES-11676-250301

2. Pacheco-Romero, M., Kuemmerle, T., Levers, C., Alcaraz-Segura, D., and Cabello, J. Integrating inductive and deductive analysis to characterize archetypical social-ecological systems and their changes. *Landscape and Urban Planning*, in review.

Otras publicaciones

3. van Oudenhoven, A.P.E., Schröter, M., Drakou, E.G., Geijzendorffer, I.R., Jacobs, S., van Bodegom, P.M., Chazee, L., Czúcz, B., Grunewald, K., Lillebø, A.I., Mononen, L., Nogueira, A.J.A., **Pacheco-Romero, M**., Perennou, C., Remme, R.P., Rova, S., Syrbe, R., Tratalos, J.A., Vallejos, M., and Albert, C. (2018). Key criteria for developing ecosystem service indicators to inform decision making. *Ecological Indicators*, 95(1): 417-426. https://doi.org/10.1016/j.ecolind.2018.06.020.

4. Vallejos, M., Aguiar, S., Baldi, G., Mastángelo, M.E., Gallego, F., **Pacheco-Romero, M**., Alcaráz-Segura, D., and Paruelo, J.M. (2020). Social-Ecological Functional Types: Connecting People and Ecosystems in the Argentine Chaco. *Ecosystems* 23: 471–484. https://doi.org/10.1007/s10021-019-00415-4

5. López-Rodríguez, M.D., Salinas-Bonillo, M.J., Torres, M.T., **Pacheco-Romero, M.,** Guirado, E., Castro, H., y Cabello, J. (2020). Impulsando estrategias colectivas ciencia-gestión-sociedad para conservar el hábitat de *Ziziphus lotus* (Hábitat Prioritario 5220). *Revista Ecosistemas* 29(1):1890. https://doi.org/10.7818/ECOS.1890

6. Cabello, J. López-Rodríguez, M.D., **Pacheco, M**., Torres M.T., y Reyes, A. (2019). Valores y argumentos para la conservación de la diversidad vegetal de Sierra Nevada. En: Peñas, J. y Lorite, J. (eds.), *Biología de la Conservación de plantas en Sierra Nevada. Principios y retos para su preservación*. Editorial Universidad de Granada, Granada, pp. 345-363. ISBN 9788433865120.

El concepto de sistema socio-ecológico (SSE), que reconoce formalmente el acoplamiento entre los sistemas humanos y naturales, proporciona una aproximación integradora fundamental para hacer frente a los desafíos medioambientales que plantea el Antropoceno, y constituye un pilar básico para desarrollar las ciencias de la sostenibilidad. Esta Tesis Doctoral proporciona avances conceptuales y metodológicos en torno a dos ámbitos fundamentales para operacionalizar el concepto de SSE y construir conocimiento más comparable y generalizable en investigación socio-ecológica: la identificación de variables clave para el estudio de los SSE, y la cartografía y caracterización de SSE.

CAESCG
CENTRO ANDALUZ PARA LA EVALUACIÓN
Y SEGUIMIENTO DEL CAMBIO GLOBAL