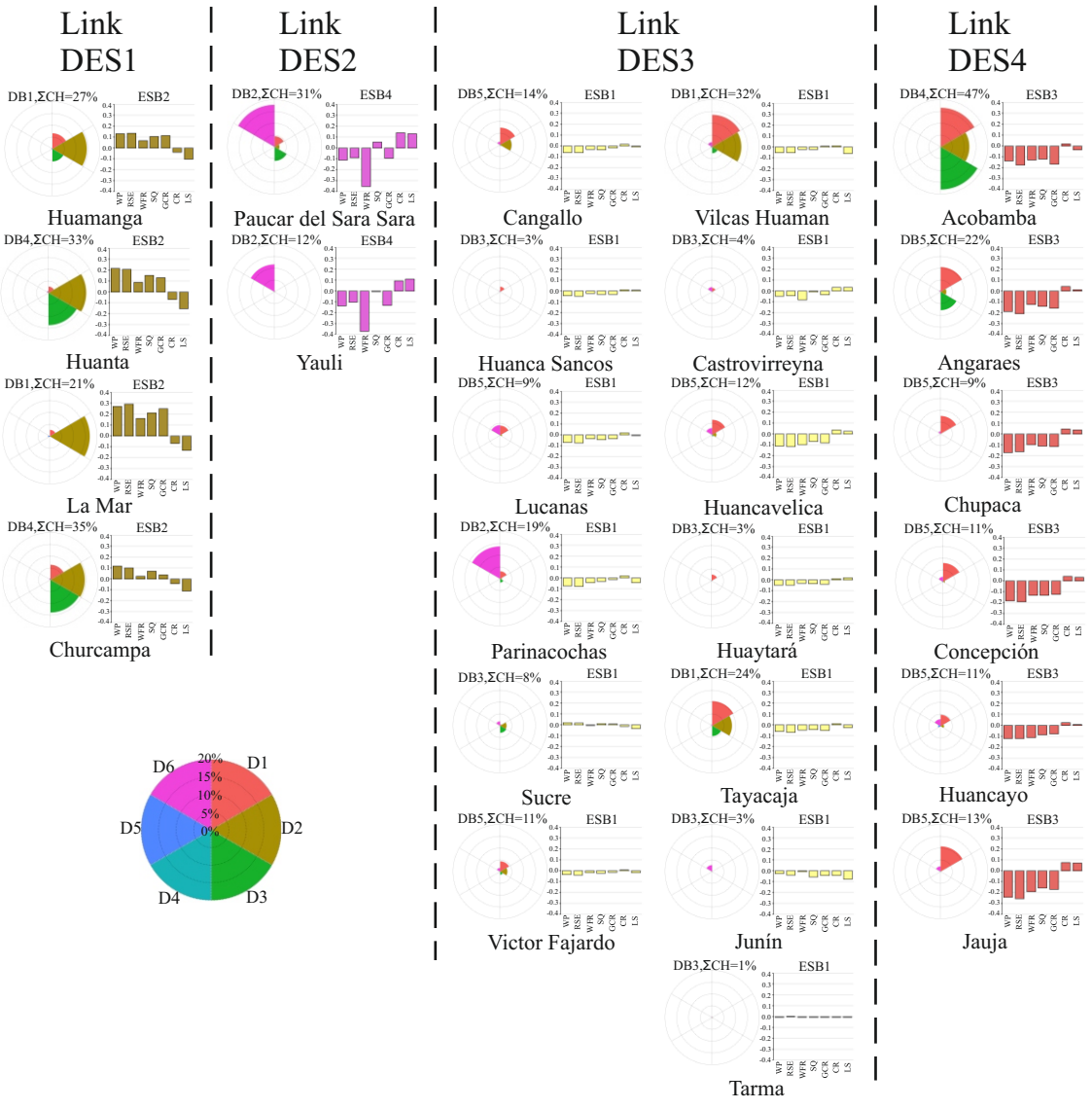
Land-change dynamics and ecosystem services using expert-based assessment and GIS: methodological implications for improving decision-making



A thesis submitted for the degree of PhD in Transportation Infrastructures and Territory

Author: Santiago Madrigal Martínez
Director: Josep Lluís Miralles i García

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Valencia, mayo de 2021

This is a Ph. D. thesis based on the compilation of scientific articles according to the rules established by Universitat Politecnica de Valencia. The doctoral candidate has contributed to the whole process of this research work, including the design of the research, analysis of the results, writing, and editing of each manuscript. He is the main author and has carried out communication with the editor of each journal. Also, he has answered the questions raised by the reviewers of the articles. Listed below are the three scientific articles and the book chapter resulting from the developed research:

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Dr. Josep Lluís Miralles i García, Tenured Lecturer of the School of Civil Engineering in the Department of Urbanism, Universitat Politecnica de Valencia, AUTHORIZE:

The presentation of the Doctoral Thesis in the form of a compendium of articles and entitled "Land-change dynamics and ecosystem services using expert-based assessment and GIS: methodological implications for improving decision-making", carried out by Santiago Madrigal Martínez, under my immediate direction and supervision, in the Department of Urbanism, and presented for the degree of International Doctor by the Universitat Politecnica de Valencia.

And for the record, in compliance with current legislation, I sign this authorization in Valencia.

Dr. Josep Lluís Miralles i García

According to point 15 of RD 99/2011, this Doctoral Thesis may opt to the mention «International Doctorate», complying, among others, the following conditions:

a) During the training period for the doctorate, the student completed a stay of three months outside Spain conducting research at a prestigious research center, “Centro de Competencias del Agua” (Peru). The visit and activities were endorsed by the supervisor and approved by the academic committee, and incorporated into the document describing the doctoral activities of the student.
b) The thesis has been reported on by a minimum of two expert doctors belonging to a foreign institution of higher education or research center.
c) At least one expert with a doctorate is from a foreign institution of higher education or a research center that is separate from the institution mentioned in above paragraph (a), and forms part of the tribunal that evaluates the thesis.

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ABSTRACT

Mountain ecosystem services have gained relevance among scientists, managers, and policy-makers worldwide; but, human activities are threatening its conservation, particularly land-changes due to increased urbanization, agricultural expansion and deforestation. The high-Andean Puna is a representative mountain ecosystem that is facing these serious and growing challenges. The high-Andean Puna, whose main social-ecosystems consist of natural grassland, shrubland and agricultural areas, can provide multiple regulating ecosystem services influenced by the land cover/use type and their dynamics.

In this context, we explored the dynamics between the representative land-cover classes and its potential to provide ecosystem services in the high-Andean moist Puna over time. We completed a spatiotemporal analysis that describes how different patterns of 6 land-change dynamics impact on the supply of 7 ecosystem services over a period of 13 years (from 2000 to 2013), and across 25 provinces. Moreover, in order to improve the management of ecosystem services, we addressed the effects of applying two cluster analyses (static and dynamic) for assessing bundles of ecosystem services across four different scales of observation (two administrative boundaries and two sizes of grids: 0.25 and 9 km^2).

Overall, this study provides an approach to facilitate the incorporation of ES at multiple scales allowing an easy interpretation of the region development that can contribute to land management actions and policy decisions.

RESUMEN

Los servicios ecosistémicos de montaña han adquirido importancia entre los científicos, los administradores y los encargados de formular políticas de todo el mundo; sin embargo, las actividades humanas están amenazando su conservación, en particular los cambios en el uso del suelo debido al aumento de la urbanización, la expansión agrícola y la deforestación. La Puna Altoandina es un ecosistema montañoso representativo que enfrenta estos serios y crecientes desafíos. La Puna Altoandina, cuyos principales socio-ecosistemas consisten en pastizales naturales, matorrales y zonas agrícolas, puede proporcionar múltiples servicios ecosistémicos influenciados por el tipo de cobertura terrestre y sus dinámicas.

En este contexto, se han explorado las dinámicas entre los usos representativos de la superficie terrestre y su potencial para proporcionar servicios ecosistémicos en la Puna húmeda Altoandina a lo largo del tiempo. Asimismo, se ha completado un análisis espacio-temporal que describe cómo diferentes patrones de 6 dinámicas de cambio del uso del suelo impactan en la provisión de 7 servicios ecosistémicos durante un período de 13 años (de 2000 a 2013), y en el territorio de 25 provincias. Además, con el fin de mejorar la gestión de los servicios ecosistémicos, abordamos los efectos de aplicar dos análisis "clúster" (estáticos y dinámicos) para evaluar los conjuntos de servicios ecosistémicos en cuatro escalas de observación diferentes (dos ámbitos administrativos y dos tamaños de pixel geográfico: 0.25 y 9 km^2).

En general, este estudio proporciona un enfoque para facilitar la incorporación de los servicios ecosistémicos a múltiples escalas que permite una interpretación fácil del desarrollo de la región y que puede contribuir a mejorar las acciones para la gestión del uso del suelo y las decisiones de política ambiental.

RESÚM

Els serveis ecosistèmics muntanya han adquirit importància entre els científics, els administradors i els encarregats de formular polítiques de tot el món; no obstant això, les activitats humanes estan amenaçant la seua conservació, en particular els canvis en l'ús del sòl a causa de l'augment de la urbanització, l'expansió agrícola i la desforestació. La Puna Altoandina és un ecosistema muntanyenc representatiu que enfronta aquests seriosos i creixents desafiaments. La Puna Altoandina que els seus principals soci-ecosistemes consisteixen en pasturatges naturals, matolls i zones agrícoles, pot proporcionar múltiples serveis ecosistèmics influenciats per les diferents categories de cobertura terrestre y els seus dinàmiques.

En aquest context, s'han explorat les dinàmiques entre els usos representatius de la superfície terrestre i el seu potencial per a proporcionar serveis ecosistèmics en la Puna humida Altoandina al llarg del temps. Així mateix, s'ha completat una anàlisi espai-temporal que descriu com diferents patrons de 6 dinàmiques de canvi de l'ús del sòl impacten en la provisió de 7 serveis ecosistèmics durant un període de 13 anys (de 2000 a 2013), i en el territori de 25 províncies. A més, amb la finalitat de millorar la gestió dels serveis ecosistèmics, abordem els efectes d'aplicar dues anàlisis "clúster" (estàtics i dinàmics) per a avaluar els conjunts de serveis ecosistèmics en quatre escales d'observació diferents (dos àmbits administratius i dues grandàries de píxel geogràfic: 0.25 y 9 km^2).

En general, aquest estudi proporciona un enfocament per a facilitar la incorporació dels serveis ecosistèmics a múltiples escales que permet una interpretació fàcil del desenvolupament de la regió i que pot contribuir a millorar les accions per la gestió de l'ús del sòl i les decisions de política ambiental.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS/ACRONYMS

ES	**Ecosystem Services**
GIS	**Geographic Information System**
LULC	**Land Use/Land Cover**
CLC	**Corine Land Cover**
SD	**Standard Deviation**
SE	**Standard Error**
RDA	**Redundancy Analysis**
CUF	**Continuous Urban Fabric**
AA	**Agricultural Areas**
LF	**Low Forest**
FP	**Forest Plantation**
NG	**Natural Grassland**
SHL	**Shrublands**
SVA	**Sparsely Vegetated Areas**
GL	**Glaciers**
PhAW	**Peatbogs and high-Andean Wetlands**
WB	**Water Bodies**
WC	**Water Courses**
WP	**Water Purification**
RSE	**Regulation of Soil Erosion**
WFR	**Water Flow Regulation**
SQ	**Soil Quality**
GCR	**Global Climate Regulation**
CR	**Crops**
LS	**Livestock**
D1	**Agricultural expansion**
D2	**Agricultural de-intensification**
D3	**Deforestation**
D4	**Urbanization**
D5	**Afforestation**
D6	**Natural processes**
DB	**Cluster of land-change Dynamics**

ESB	**Ecosystem Services Bundle**
DES	**Links between land-change dynamics and ES trends**

CHAPTER 1. INTRODUCTION

1.1. Ecosystem services in the high-Andean moist Puna

Ecosystem services (hereafter ES), defined as the benefits that nature provides to the population (MA, 2005), has become an effective boundary object for the integration of ecosystem conservation opportunities (Abson et al., 2014). Mountain ecosystems services have gained relevance among scientists, managers, and policy-makers worldwide (Egarter Vigl et al., 2017; Feixiang et al., 2016; Grêt-Regamey et al., 2012; Madrigal-Martínez & Miralles i García, 2019a). However, human activities are threatening their conservation (MA, 2005), particularly land-cover changes due to increased agricultural intensification, urbanization, and deforestation. These rapid land-cover changes that occurred around the world have received much attention from scientists, and there were numerous studies focused on various research issues at different spatial scales (Du et al., 2014; Kuemmerle et al., 2016; E. Lee et al., 2018). This growing scientific production has been possible by free and open access data (Wulder et al., 2018) and the use of remote sensing and geographic information system (GIS) tools (Lu et al., 2004). GIS provides a flexible environment for rapidly developing data processing and analyzing for change detection in a study area.

In Peru, the high-Andean Puna is a representative mountain ecosystem that is facing these serious and growing challenges. This ecosystem is composed of two well-defined phytogeographic regions: the moist Puna and the xerophytic Puna (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a). The moist Puna (Peru and Bolivia) has been occupied, and its resources profited during several millennia by Andean civilizations (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a; K. R. Young, 2009). This mountain environment, where its main social-ecosystems consist of natural grassland, shrubland, and agricultural areas, can provide multiple ES related to the configuration of its land-cover features (Madrigal-Martínez & Miralles i García, 2019b).

In this sense, land use/land cover (hereafter LULC) models offer high performance for explaining the provision of individual ES (Burkhard et al., 2009). Evaluation of ES using LULC maps and expert estimation is worldwide extended (Jacobs et al., 2015), but scarce examples are found in mountain regions (e.g. (Balthazar et al., 2015; Bhandari et al., 2016)) and none in the phytoregion of moist Puna. This technique, the ES matrix model (Burkhard et al., 2009), could overcome the lack of data present in the region (Boillat et

al., 2017) and solve the necessity of more ES appraisals in highland territories (Grêt-Regamey et al., 2012). We quantified the potential capacity of the moist Puna to provide seven ES (Table 1; five regulating and two provisioning services).

Ecosystem services	Description
Regulating	
Water purification	Regulation of the chemical condition of freshwaters by living processes. e.g., Use of buffer strips along water courses to remove nutrients in runoff.
Regulation of soil erosion	Control of erosion rates. e.g., The capacity of vegetation to prevent or reduce the incidence of soil erosion.
Water flow regulation	Hydrological cycle and water flow regulation (Including flood control) e.g., The capacity of vegetation to retain water and release it slowly.
Soil quality	Decomposition and fixing processes and their effect on soil quality. e.g., Decomposition of plant residue; N-fixation by legumes.
Global climate regulation	Regulation of chemical composition of atmosphere. e.g., Sequestration of carbon in tropical peatlands.
Provisioning	
Crops	Cultivated plants for nutrition, materials or energy
Livestock	Reared animals for nutrition, materials or energy

(Elaborated by the Authors - drawn from Haines-Young & Potschin, 2018)

Table 1: Description and examples of the selected ES studied in the moist Puna

Mountain landscapes provide multiple ES that vary across space and time due to changes in land use change dynamics, making necessary a spatiotemporal analysis to advance the knowledge of ES trajectories (Egarter Vigl et al., 2017; Lautenbach et al., 2011; Renard et al., 2015). This complex ecological reality, of multiple ES linked to land use in change tendencies, is clarified with ES bundles (der Biest Van et al., 2014). Bundles of ES, sets of ES co-occurring with human activities across a landscape over time (C Raudsepp-Hearne et al., 2010) can help integrating ES models and land-use planning (Crouzat et al., 2015). Moreover, to better understand how sets of ES co-occur, there is a need to assess the variables that explain this process (Meacham et al., 2016; Spake et al., 2017). At present, there are no studies of ES bundles in the high-Andean region linking clusters of land-change dynamics with bundles of ES trends to be used as a framework for improving stakeholder decisions in land planning.

Furthermore, relationships among ES depend on the scale of observation. For example, a situation of mutual enhancement among a pair of ES (synergy) at the county level could become an increase in one service at the expense of the other (trade-off) at grid-scale (Xu

et al., 2017); also, a bundle of ES characterized by a multifunctional pattern of supply at municipality level can derive in a set of ES dominated by the provision of few services at the patch scale (Ciara Raudsepp-Hearne & Peterson, 2016). These relationships can vary depending on the methods used to assess them. For example, the correlation analysis between two ES for a given time can detect a trade-off, while the same analysis between the differences in ES supply at two times detects a synergy (Tomscha & Gergel, 2016). Most of the assessments focused on a simple (static) method for estimating ES on a specific spatial scale (Lavorel et al., 2017), and few studies integrated historical analysis (e.g., in (Li et al., 2019; Madrigal-Martínez & Miralles i García, 2019b; Renard et al., 2015; Wei et al., 2019)). Thus, only a limited number of studies identified the effects of different spatial scales on ES (e.g., in (Cui et al., 2019; Dou et al., 2018; Hamann et al., 2015; Qiao et al., 2019; Ciara Raudsepp-Hearne & Peterson, 2016; Roces-Díaz et al., 2018)), but using a snapshot approach (ES assessment at a single point in time). Thus, improvement of the characterization of spatiotemporal co-occurrences of ES, applying different assessment methods at different scales of observation, can contribute to reinforcing efficient management strategies that seek to achieve win-win solutions (Howe et al., 2014).

Among the common methods for assessing ES relationships, there is correlation analysis, and cluster analysis (Deng et al., 2016; Spake et al., 2017). Correlation analysis is mostly applied to measure the degree of statistical dependency between a pair of ES for a given time to classify their relationship as a trade-off or synergy (Dade et al., 2019; H. Lee & Lautenbach, 2016). Cluster analysis is one of the main statistical methods utilized for the estimation of bundles of ES for a given time (Cord et al., 2017; Saidi & Spray, 2018). Bundles have appeared as an integrated method to assess and visualize consistent associations among multiple ES derived from the different land use and land cover types (C Raudsepp-Hearne et al., 2010). Different authors explored how the ES bundle concept contributes to including ES models into land-use planning (Crouzat et al., 2015; der Biest Van et al., 2014), to clarify the impacts of land-change dynamics on ES (Madrigal-Martínez & Miralles i García, 2019b), to identify priority areas for ES management (Egoh et al., 2011), to distinguish social preferences toward ES (Martín-López et al., 2012) or to investigate ES bundles for analyzing trade-offs (Queiroz et al., 2015; C Raudsepp-Hearne et al., 2010; K. G. Turner et al., 2014; Yang et al., 2015). Despite these increasing efforts, there are still current methodological limitations related to the understanding of how the relationships between ES changes at multiple time steps. Another lack of

knowledge is about which might be the appropriate spatial scales in empirical or modeling ES research (Birkhofer et al., 2015; Rieb et al., 2017). The different methods applied for the assessment of relationships between ES can lead to different interpretations (H. Lee & Lautenbach, 2016; Tomscha & Gergel, 2016; Vallet et al., 2018; Zheng et al., 2014). Added to this, the use of a single scale of observation on ES assessments can lead to the avoidance of relationships between ES and ignore differences in spatial patterns between them when changing analysis scales (Ciara Raudsepp-Hearne & Peterson, 2016; Roces-Díaz et al., 2018; Xu et al., 2017).

1.2. Objectives and approach

The Ph.D. project meant to address how knowing the state of the ecosystem services can help as an evaluation mechanism to reinforce the sustainable management of socio-ecological systems. To do so, we develop the research in a case study system in the central high-Andean moist Puna of Peru. The study addresses the overall aim through the following three sub-analyses and their respective research questions.

The first objective ascertains the land-use change at the provincial scale from 2000 till 2013, using a selection of eleven land use/land cover (LULC) types included in the standardized nomenclature of the Corine Land Cover (CLC) for Peru. Next, the importance of social-economic driving factors on the land-use change in two-time periods is determined. The work detailed in this analysis resolve the following aim questions:

- Which are the main anthropogenic land-use changes?
- Which are the significant social-economic drivers that explain land-use changes?

The second objective establishes the variations in the supply of ecosystem services due to land-change dynamics in the study area. A spatiotemporal analysis is developed to reach the proposed objective. It describes how different patterns of six land-change dynamics impact the supply of seven ES over time (from 2000 to 2013), and across 25 provinces in the central high-Andean moist Puna of Peru. The study assesses the following research questions:

- Which is the maximum capacity of each land use/land cover unit to supply ecosystem services?
- Which are the associations between clusters of land-change dynamics and ecosystem service bundles?

- Which are the explanatory variables that best predict the associations between clusters of land-change dynamics and ecosystem service bundles?

The third objective examines the differences in applying two frameworks (static and dynamic) for the assessment of bundles of ES at four scales of observation over time, to provide new insights for better management of ES. To achieve this objective, two questions are addressed:

- Is the grouping of ES into ES bundles affected by the method applied for assessing them?
- Is the grouping of ES into ES bundles influenced by the scale of observation over time?

CHAPTER 2. MATERIALS AND METHODS

2.1. The study site: the central high-Andean moist Puna

The selected area is a sector of the Peruvian high-Andean mountains, the central division of the phytoregion of the moist Puna (64,025 km^2), comprised within the administrative boundaries of 25 provinces in the departments of Junín, Huancavelica, and Ayacucho (Fig 1). The altitude ranging from 2 000 to 5 400 masl. Its main social-ecosystems consist of natural grassland, shrubland, and agricultural areas (K. R. Young, 2009), that are threatened by human activities (MA, 2005), as agricultural intensification, grasslands extent, afforestation, and urbanization (Lambin et al., 2003). The provincial area ranged from 724 to 10,999 km^2, with an average of 2561 km^2. These provinces define a highly populated mountain ecosystem (population at the end of 2017 was 2 096,156 (INEI - National Institute of Statistics and Informatics, n.d.-b)) that has been occupied and its resources profited during several millennia by Andean civilizations (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a; K. R. Young, 2009). This landscape is dominated by an expansion of livestock breeding in the upper lands, and an increase in farming in the fertile lowlands. It is typical of many mountain agroecosystems across the world. Then, the economic activity that predominates is agriculture, characterized by the cultivation of tubers such as potatoes, maca, mashua, oca, and olluco. The natural pastures present in the territory make an optimal fodder for alpacas, llamas, vicuñas, sheep, and cattle.

Most of this territory is embedded within the Mantaro river basin, which includes ecosystem services associated with agricultural practices (crops and livestock provision, regulation of soil erosion and maintenance of soil quality), hydrological cycle (water purification, and water flow regulation), and climate regulation. In general terms, there are periods of very severe precipitation between December and April, reaching averages between 500 and 900 mm (Gobierno Regional de Huancavelica, 2013). However, there are also areas where there is no rain that brings severe droughts. In addition, the longitudinal distribution of geological faults is one of the main agents for the occurrence of earthquakes.

Regarding the property of the land, 50% (32,814 km^2) of the territory belongs to peasant communities (Gobierno Regional de Ayacucho, 2013; Gobierno Regional de Huancavelica, 2013). The peasant community is an institution made up of peasant

families that organize themselves under certain social and cultural norms and parameters. The community is responsible for the management of the natural resources under its care.

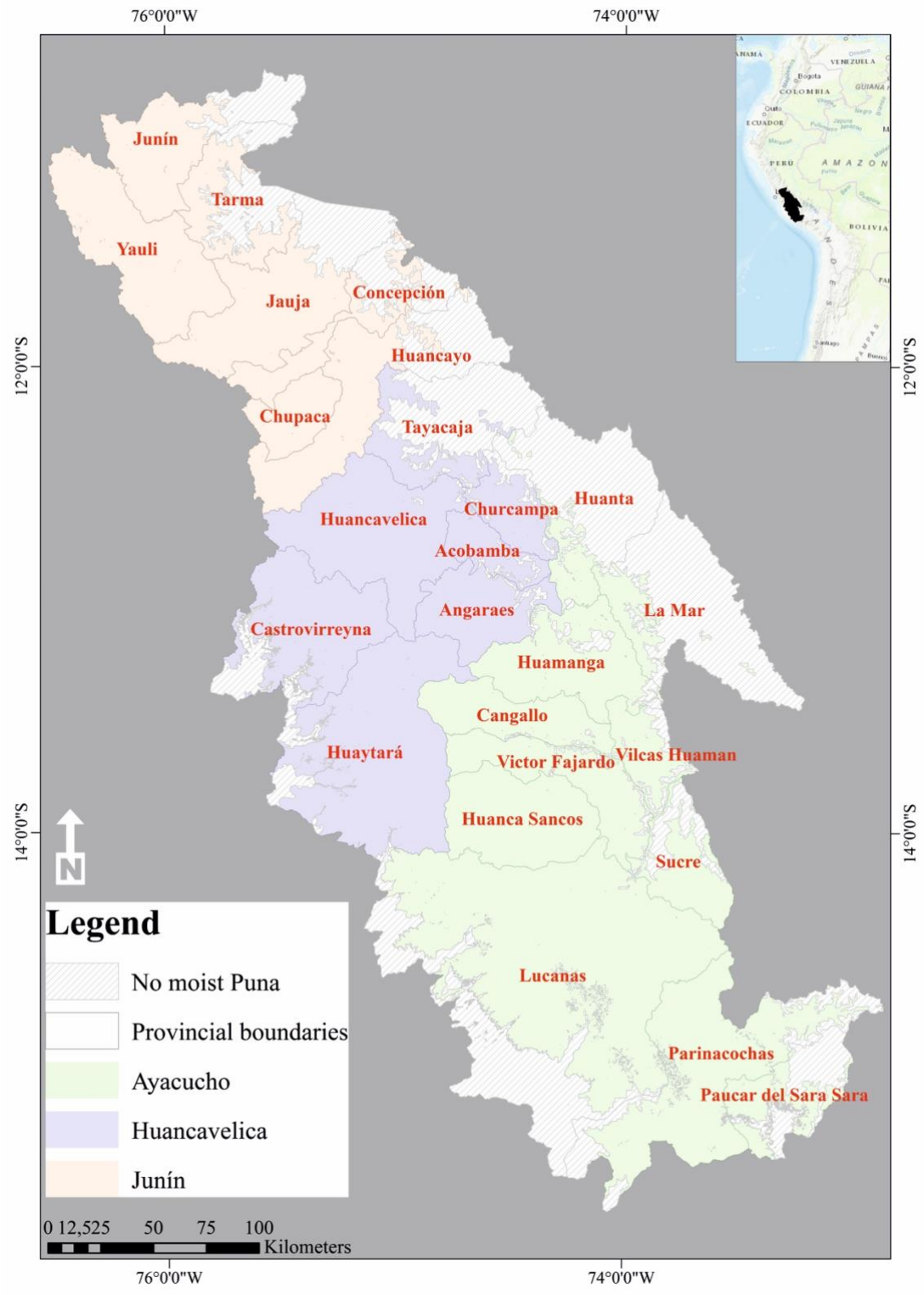


Figure 1: The central high-Andean moist Puna.

2.2. Identification of land use/land cover units

The identification of the LULC units for the high-Andean moist Puna was achieved from three-time map sources: the map of high-Andean ecosystems in 2000 (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a), the official flora cover map from 2009 (Ministry of Environment, 2012), and the official flora cover map from 2013 (Ministry of Environment, 2015b). Complementary, the data from the official Peruvian forest map (National Institute of Natural Resources, 2000) was used to clarify natural grassland and sparsely vegetated areas uncovered in the map of high-Andean ecosystems. According to the official sources, the maps were submitted to a verification and field survey procedure for improving the accuracy of the land use/land cover classification. However, the three maps showed differences in the nomenclature and the geographical scale that made necessary a generalization of the land use/land cover classes and the achieving of a harmonized legend. This integrated legend was manually obtained and included the categories of the Peruvian standardized nomenclature of the Corine Land Cover (CLC). Table 2 shows the harmonization of the three-time step features to obtain a common legend of eleven moist Puna LULC units. The description of satellite images, mapping scale, minimum mapping area, and type of data of the three source maps are specified in Table A1 (see Appendix II).

CLC code	LULC units	Features	Data Source
1.1.1.	Continuous urban fabric	• Cities and settlements	(1) (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a)
		• Urban area	(2)(Ministry of Environment, 2012); (3)(Ministry of Environment, 2015b)
2.	Agricultural areas	• Human at work areas	(1)
		• Crops	(2)
		• Andean agriculture	(3)
3.1.1.	Low forest	• Inter-Andean xeric montane forest and shrublands • Low high-Andean forest • High-montane low forest and shrublands	(1)
		• Queñoal • Inter-Andean xeric forest	(2)
		• Inter-Andean xeric forest • High-Andean relict forest • Meso-Andean relict forest	(3)
3.2.	Forest plantation	• Human at work areas	(1)
		• Afforestation	(2)
		• Forest plantation (pinus and eucalyptus species)	(3)
3.3.1.	Natural grassland	• High-Andean grassland • High-montane grassland	(4)(National Institute of Natural Resources, 2000); (3)
		• High-Andean grassland • Puna grass	(2)
3.3.2.	Shrublands	• Inter-Andean xeric montane shrublands • Inter-Andean xeric shrublands • High-montane shrublands • High-Andean shrublands	(1)
		• Shrublands	(2); (3)
3.4.3.	Sparsely vegetated areas	• Tundra	(4); (2)
		• High-Andean areas with rare vegetation	(2); (3)
3.4.5.	Glaciers	• Nival	(1)
		• Glaciers	(2); (3)
4.1.2.	Peatbogs and high-Andean wetlands	• High-Andean wetlands	(1); (2); (3)
5.1.1.	Water courses	• Water bodies	(1)
		• River	(2); (3)
5.1.2.	Water bodies	• Water bodies	(1)
		• Lagoons and lakes	(2); (3)

Table 2: Land use/cover units resulting from the features of the three-time step data

A general description of the ecosystems in the study area is as follow (Ministry of Environment, 2018):

3.1.1. Low forest

- High-Andean relic forest (Queñoal and others). Forest dominated by associations of "queñua" (Polylepis spp.), extending over more than 0,5 hectares, with trees more than 2 meters high and a floor cover of more than 10 %; commonly restricted to rocky slopes or ravines; current distribution in patches or islands of vegetation.
- Meso-Andean relict forest. Represented by pure or mixed communities of Escallonia resinosa "chachacoma" or "karkac" and Escallonia myrtilloides "tasta". It extends for more than 0,5 hectares, with trees of more than 2 meters in height and a soil cover greater than 10%; commonly distributed as patches restricted to special localities, on mountainous slopes with moderate to strong slopes.
- Inter-Andean xeric montane forest. Forest characterized by deciduous trees distributed along the inter-Andean valleys, including herbaceous species in the lower stratum.

3.3.1. Natural grassland

Herbaceous vegetation consisting mainly of grasses, scrublands, and some scattered shrubby associations. It can occupy flat or undulating terrain or gentle to moderate sloping hills. It has a coverage of 35-50%, and height generally does not exceed 1.5 meters.

3.3.2. Shrublands

It is characterized by woody and shrubby vegetation of variable composition and structure, with a cover of soil more than 10 %, and height above the ground does not exceed 4 meters.

3.4.5. Glaciers and 3.4.3. Sparsely vegetated areas

Ecosystem located above 4 500 masl. Soils cryopeated and exposed with abundant brittle (thaw). Low and dispersed vegetation (usually not more than 30 or 40 cm), represented by scarce grasses, Asteraceae, lichens, and stuffed plants. It should be noted that there are periglacial areas that are no longer associated with glaciers. Glaciers are ice masses that accumulate in the highest floors of the mountain ranges (above the 5 000 masl).

4.1.2. Peatbogs and high-Andean wetlands

Peatbogs and high-Andean wetlands. Hydrophilic herbaceous vegetation, which occurs on flat, depressive, or slightly inclined soils; permanently flooded or

saturated with running water (poor drainage), with dense and compact vegetation always green, cushioned, or cushioned; the appearance of the vegetation corresponds to grasses from 0.1 to 0.5 meters. Organic soils can be deep (peat).

2.3. Analyzing land-use change dynamics

Land-use changes between 2000 and 2013 were calculated by means of a transition matrix obtained after using ArcGIS 10.3 (ESRI, 2014). The matrices of land-use transition were established for two-time periods, including 2000–2009 and 2009–2013. Each transition matrix gathered the quantity of land that was converted from each LULC unit to any other or units that remain unchanged in the study periods. Changes of interest in this study were related to agricultural areas, grassland extent, and forestland size. These variations were further calculated obtaining increased/decreased extents. Next, to measure and compare the intensity of land-use changes between provinces, the proportion of area increase and extent decrease (of the chosen classes) were calculated for the two-time periods. The following formula was used to calculate the index for area increase (1.1) and area decrease (1.2):

$$Pi_n = \frac{LULC_{nt2}}{AT_n} \quad (1.1)$$

$$Pd_n = \frac{(LULC_{nt2})_{nt1} - LULC_{nt1}}{AT_n} \quad (1.2)$$

where $LULC_{nt2}$ is the new area (km^2) of the chosen class in a province *n* at the final year *t2;* $(LULC_{nt2})_{nt1}$ is the overlapping area of a given class in both years; $LULC_{nt1}$ is the area (km^2) of the chosen class in a province *n* at the initial year *t1*; AT_n is the total area of the province *n*.

This index gave a relative measure of the change that was ranked in five levels of equal intervals representing the intensity of expansion/contraction of each chosen category at the provincial scale. Furthermore, we performed Pearson's correlation (r_p) to assess the pairwise relations between LULC categories for the two-time periods at the provincial scale, using R software (R Development Core Team, 2016).

The transitions assessed in the former analysis were grouped to obtain main land-change dynamics. Subsequently, their proportion of change at the province scale was estimated with Excel 2015. Furthermore, the consistencies between the different time-period models were evaluated with kappa statistics (Cohen, 1960; Landis & Koch, 1977).

2.4. Ecosystem services potential supply

The ES potential supply of the study area is assessed using the capacity matrix method. The ES matrix is an expert-based estimation technique (Burkhard et al., 2009), that is extensively used to overcome data scarcity (Depellegrin et al., 2016; Montoya-Tangarife et al., 2017). However, uncertainties are included in the scoring assessment (Hou et al., 2013; Jacobs et al., 2015). In order to minimize this, Campagne *et al.*, (2017) measured that 30 experts are enough to get a stable mean without inconsistencies and the variability of the final scores is constant after 15 experts, decreasing the standard error when increasing the expert panel size. For this study, 43 national and international experts (see respondent pool particulars in Table A2, Appendix II), that have published scientific or technical works about ES or related ecological processes in the moist Puna, were individually consulted to rank the ES potential supply associated with a specific LULC on a relative scale, ranging from 0 (no relevant ES potential supply) up to 5 (very high ES potential supply). Burkhard *et al.*, (2012) conceptualize the ES potential as the hypothetical maximum capacity of a LULC to supply a specific ES. Our matrix linked eleven LULC classes and seven ES, including regulating (n = 5) and provisioning (n = 2). To increase confidence, experts fulfilled only the LULC/regulating ES pairs that were surely in their judgments. Each response was collected and deprived of outliers using the interquartile range method (see Table A3, Appendix II). Then, a final score was computed using the mean. The potential supply of the LULC in provisioning services was achieved from official model results included in land planning instruments of the administrative departments under study (see Table A4, Appendix II). The ecosystem services were set as constant values assuming that land units are in good condition during the study period. The seven selected ES include site-specific services from two main categories (five regulating and two provisioning) identified by the Common International Classification of Ecosystem Services (Haines-Young & Potschin, 2018): two regulating services related to mediation of flows (regulation of soil erosion and water flow regulation); one ES related to filtration, sequestration, storage or accumulation by ecosystems (water purification); two services linked to the maintenance of physical, chemical, biological conditions (soil quality and global climate regulation) and, finally, two provisioning services related to nutrition (crops and reared animals).

2.5. Scaling method

The ES and ΔES (the amounts of changes in ES values at two times) maps were derived from the matrix model and upscaled to four spatial scales: two administrative divisions (provincial and municipal) and two grids (coarse and fine). The four spatial scales were selected for their particular importance in spatial planning and ecosystem services mapping. The provincial level (with an area of ~10^3 km^2) has a central role in the Peruvian planning system binding national and departmental directives with local interventions (Organic Law of Municipalities No. 27,972). The municipal level (with an area of ~10^2 km^2) is where land-use management in urban areas and the countryside are made. Coarse-grid resolution (with an area of 9 km^2) was chosen because it explores patterns of ecosystem services and approximates a locality. A fine-grid (with an area of 0.25 km^2) was included because it is where individual land-use management and land-cover changes occur. This spatial scale was decided as the finest because, according to the Corine Land Cover approach and the official flora cover map from 2009 (Ministry of Environment, 2012), corresponds to the minimum mapping area of the study maps (geographical scale of 1:100 000). Moreover, both grid resolutions are important for planning green infrastructure to support human well-being.

The administrative areas were calculated using boundaries from the Peruvian National Institute of Informatics and Statistics. The 25 provincial units range from 724 to 10,999 km^2 (with an average of 2561 km^2), whereas the municipality units (n=175) vary from 5 to 2176 km^2 (with an average of 158 km^2). On the other hand, the coarse-grid (3 × 3 km) and the fine-grid (0.5 × 0.5 km) resolutions were both generated using the Fishnet tool and the Geoprocessing tool in ArcGIS 10.3 (ESRI, 2014). The coarse-grid comprises 3019 cell units, while the fine-grid has 110,343 spatial units. The cells with at least 95% of their area within the boundaries of the study area were included.

After this, each of the four maps of spatial units was separately intersected with every LULC map of each year (2000, 2009, and 2013), obtaining 12 maps. Next, the ES matrix was applied on these 12 maps deriving 84 maps of ES potential supply. These potential supply maps were aggregated to their corresponding spatial resolution by using Equation (2.1):

$$ES_{ns} = \frac{\sum_{i=1}^{S} (ES_i \times A_i)}{S} \quad (2.1)$$

where *ESns* is the potential supply of a given spatial unit *s* for a given ecosystem service *n*, ES_i is the score assigned to a given LULC unit *i*, and A_i is the area of that given LULC unit *i* within the given spatial unit *n*. *S* is the total area of the given spatial unit. Figure A5 (see Appendix II) provides a graphical sample of the scaling method.

Lastly, to obtain the upscaled *ΔES* values over the two periods, from 2000 (t_1) to 2009 (t_2) and 2009 (t_2) to 2013 (t_3), Equation (2.2) was used:

$$\Delta ES_{ns} = ES_{ns}(t_{k+1}) - ES_{ns}(t_k) \quad (2.2)$$

where ΔES_{ns} is the potential supply of a given spatial unit *s* for a given ecosystem service *n* of the final year t_{k+1} minus the potential supply of that given spatial unit *s* for the given ecosystem service *n* of the initial year t_k.

2.6. Cluster analyses

2.6.1. Cluster analysis for land-change dynamics

Clusters of land-change dynamics (DB) were delineated with the percentage of LULC change accounted for the dynamics on each administrative boundary. The cluster analysis was done with the "affinity propagation" method, a graph-based clustering algorithm, that find the optimal number of clusters (Frey & Dueck, 2007) using R (R Development Core Team, 2016). The spatial distribution of bundles was mapped with ArcGIS 10.3 (ESRI, 2014).

2.6.2. Cluster analyses for ecosystem services

Cluster analysis was selected for assessing bundles of ES at each scale of observation. This method was computed two times: (1) using the ES values at the three dates (2000, 2009, 2013), and (2) using the ΔES values for the two periods (2000–2009, 2009–2013). Then, to identify differences, the results of each assessment were compared.

The best number of clusters was determined using the "NbClust" R package (Charrad et al., 2015) configured with the combination of "euclidean" distance measure, "kmeans" method, "alllong" index, and a significance value of 0.1 for Beale's index. This package

was run (n = 4) with ES and ΔES values at the provincial and municipal levels. The majority of indices proposed three clusters as the best number in all datasets. Bundle types were identified applying a k-means cluster analysis run with 10,000 iterations in R (R Development Core Team, 2016). The k-means cluster analysis grouped the values in three specific combinations of ES. For later comparisons, the bundles were named: bundle type 1, bundle type 2, and bundle type 3. Each bundle type was drawn using Excel 2015. The different aspects of bundles were analyzed with standard metrics (Table 3). Then, the results were compared to identify differences (effects) that can establish trends. To estimate the configuration metrics, Excel 2015 was used. The spatial patterns and historical trajectories were computed using ArcGIS 10.3 (ESRI, 2014).

Aspect	Metric	Description
Configuration	True Diversity (Order 2) (^2D)	The diversity of a set of ES provided in a given bundle type is calculated as the effective number of ecosystem services based on Hill numbers [61,62]. For the "dynamic bundles", we used the absolute value of each amount of change in ES specified by a given bundle. This metric was included because it affords a stable, clearly understood, and sensitive overall similarity measure supporting cross-study assessments [11,62].
	Abundance (N)	The sum of the absolute value of each ES (or ΔES) specified by a given bundle type. The sum represents an overall level of the provisioning of services (or of the change in services). High absolute values thus indicate zones with a comparatively high supply of (or change in) multiple services, while low values indicate the opposite. This metric was included in the bundle analysis because policies are intended to protect the overall level of ES provision rather than, or in addition, to the provision of individual services.
Spatial patterns	Percentage of land	The proportional abundance of a given bundle type in a given year or a given period across the study area. It is a landscape metric that acts as a proxy for change, thus allowing for the interpretation of spatial patterns over time and space. This metric measured the results of both cluster analyses.
Historical trajectories	Percentage of land change	The proportion of land changing from one bundle in a year or period *t* to another in a year or period *t+1* on the same spatial scale. This metric measured the results of both cluster analyses.

Table 3: Metrics (and their description) used for the achievement of the aspects of bundles.

Additionally, the relationships between individual pairs of ES (n=21 pairs) through time were achieved with Spearman's rho using the ES trend values for each time period. Significant correlation ($p < 0.05$) in negative relationships indicated trade-offs, whereas positive interactions were defined as synergies.

2.7. Associations between clusters of land-change dynamics and ecosystem service trends

To assess the links between clusters of land-change dynamics and bundles of ES trends, the spatial correspondence between the models was measured by overlap analysis. Then, we gathered the overlapped clusters according to the number of partitions obtained with "affinity propagation" method (Frey & Dueck, 2007) using R (R Development Core Team, 2016). Lastly, the land-change dynamics that best explained the ES trends were determined using RDA ("vegan" R package and the function "ordistep" (R Development Core Team, 2016)).

2.8. Determining the explanatory capacity of social-economic drivers

Two redundancy analyses (RDA) were done to determine the explanatory capacity of social-economic drivers. Values of each driver were achieved for the two time periods (2000-2009 and 2009-2013) at provincial level. The first RDA was developed for land-use changes (see Section 2.8.1.) and the second on land-changes dynamics and ecosystem services (see Section 2.8.2.). For both cases, RDA was calculated using the "vegan" R package and forward selection with function "ordistep" (R Development Core Team, 2016) after 10,000 permutations (Legendre, 2018). This method selects the model with the combination of variables with the highest R^2 and p-value.

2.8.1. Social-economic drivers for predicting land-use changes

RDA was computed to determine the importance and capacity of social-economic drivers for predicting the land-use changes during the two-time periods. The drivers considered were related to population growth, economic development and technological progress (Table 4). These variables were selected due to their role as anthropogenic drivers of ecosystem change (Nelson et al., 2006) and data availability. Data from public census statistics (INEI - National Institute of Statistics and Informatics, n.d.-b) were used to quantify each variable.

Factor	Driver	Proxy	Unit
Population growth	Population density	Log average of population density (for each period)	People/km²
Economic development	Income	Net annual income per family (averaged for each period)	S/year
Technological progress	Education	Population with completed secondary school education (averaged for each period)	%

Table 4: Factors, specific drivers and proxies used for predicting land-use changes

Population density (Number of inhabitants per square kilometer). The Peruvian National Institute of Statistics and Informatics (INEI - National Institute of Statistics and Informatics, n.d.-b) provided data for the number of inhabitants at the provincial level. We used the log average of population density per square kilometer, obtained by dividing the average (of each period) of province population size by its area. Data were compiled for each year from 2000 to 2013 for all 25 provinces. This data is online and publicly available.

Income (Peruvian currency per year). We used the average of the net annual income per family for each province. The data for all 25 is online and publicly available (INEI - National Institute of Statistics and Informatics, n.d.-b). For both periods, we compiled the available years (2003 and 2007, for the first period; and 2010, 2011, and 2012 for the second period).

Education (Percentage). The Peruvian National Institute of Statistics and Informatics (INEI - National Institute of Statistics and Informatics, n.d.) provided data for the number of population with complete secondary education in each province. We used the percentage as a proxy for education. For both periods, we compiled the available years (2003 and 2007, for the first period; and 2010, 2011, and 2012 for the second period).

2.8.2. Social-economic drivers for land-change dynamics and ecosystem services.

RDA was computed for land-change dynamics and ES trends. The evaluation determined how land-change dynamics and ES trends were related to seven potential drivers (population, mining, alpacas, goats, firewood, distance from Lima and slope). These drivers were selected due to their role as explanatory variables used for dynamics or ES modelling (e.g. Meacham et al., 2016; Mouchet et al., 2014; Renard et al., 2015; Spake et al., 2017). Deforestation in the moist Puna is related to anthropic actions like felling, firewood, fire and goat overgrazing (Naturserve, 2009). Depopulation of rural zones

explain agricultural abandonment (E. Lee et al., 2018). Population growing increase town areas affecting many ecosystem services. Slope is negative relate to livestock and crops services (Meacham et al., 2016). Mining claims have consequences on Andean ecosystems and especially on water quality (B. E. Young et al., 2008). According to location theory the distance from an urban center will define the activities for that territory.

The data was obtained from census statistics, mining database and physiography model (Table 5).

Driver	**Proxy measure**	**Unit**
Population	Log average of population density for initial period. Log average of population density for final period.	Population/km^2
Mining	Accumulated proportion of mining claims land for initial period. Accumulated proportion of mining claims land for final period.	%
Alpacas	Log average of alpaca population density for initial period. Log average of alpaca population density for final period.	Alpaca population/km^2
Goats	Log average of goat population density for initial period. Log average of goat population density for final period.	Goat population/km^2
Firewood	Log average of population density using firewood for initial period. Log average of population density using firewood for final period.	Population using firewood/km^2
Distance from Lima	Distance from Lima	km
Slope	Average of slope	%

Table 5: Details of potential drivers, proxies and units for the two-time periods (2000-2009 and 2009-2013)

Population density (Number of inhabitants per square kilometer). The Peruvian National Institute of Statistics and Informatics (INEI - National Institute of Statistics and Informatics, n.d.-b) provided data for the number of inhabitants at the provincial level. We used the log average of population density per square kilometer, obtained by dividing the average (of each period) of province population size by its area. Data were compiled for each year from 2000 to 2013 for all 25 provinces. This data is online and publicly available.

Mining (Percentage). The map of the mining cadaster of Peru provided the data (Geological Mining and Metallurgical Institute, 2018). We used the mining right entitled as a proxy of mining. In each province, the percentage of mining was calculated by dividing the accumulated area occupied by mining rights entitled by the area of the given province. For the first period, we compiled the accumulated area till from the year 1959

till 2008. For the second period, we added the area of the first period and the accumulated area from 2009 till 2013. This data is online and publicly available.

Alpacas (Population of alpacas per square kilometer). The National Census of Agriculture provided data for the number of alpacas at the provincial level. The data is online and publicly available for the 25 provinces. We used the log average of alpacas density per square kilometer, obtained by dividing the average (of each period) of province population size by its area. For the year 2000, we used the available data of the year 1994 (INEI - National Institute of Statistics and Informatics, n.d.-a). For the year 2013, we used the data compiled from 2012 (INEI - National Institute of Statistics and Informatics, n.d.-a). While for the year 2009, we calculated an annual rate projected from the available data.

Goats (Population of goats per square kilometer). The National Census of Agriculture provided data for the number of goats at the provincial level. The data is online and publicly available for the 25 provinces. We used the log average of goats density per square kilometer, obtained by dividing the average (of each period) of province population size by its area. For the year 2000, we used the available data of the year 1994 (INEI - National Institute of Statistics and Informatics, n.d.-a). For the year 2013, we used the data compiled from 2012 (INEI - National Institute of Statistics and Informatics, n.d.-a). While for the year 2009, we calculated an annual rate projected from the available data.

Firewood (Population using firewood per square kilometer). The National Household Survey (INEI - National Institute of Statistics and Informatics, 2014) provided data for the percentage of inhabitants using firewood at the departmental level. The data is online and publicly available from 2002 to 2013 for the three administrative departments. To downscale the data to the provincial level, we multiplicate the percentage of departmental level by the population at the provincial level. We used the log average of population density using firewood per square kilometer, obtained by dividing the average (of each period) by the area of a given province.

Distance from Lima (Kilometer). We used the web google maps to identify the shortest road between the capital of each province and Lima.

Slope (Percentage). We used the shapefiles of slope provided by the Economic and Ecological Zonings of Junin, Huancavelica, and Ayacucho (Ministry of Environment, n.d.-a). We calculated the average slope within each province.

2.9. Sensitivity analysis

2.9.1. Testing the variability of ES matrix scores

A sensitivity analysis was performed using descriptive statistics to prove the robustness of the regulating ES matrix. The standard deviation (SD) and the standard error (SE) were calculated from expert scores with the intention of ascertaining variability of the responses and uncertainty around the mean values, respectively. For variability control, given that match expert scores denote null SD, the answers were ranked in two categories, very low variability for SD ≤1 and low variability for SD higher than 1 and lower than 2. On the other hand, the uncertainty assessment was completed developing two sensitivity matrices with the expert scores ± SE (matrix 1 with expert scores +SE and matrix 2 with expert scores –SE). The kappa values were computed to obtain the degree of agreement between the ES regulating matrix and the sensitivity matrices.

2.9.2. Sensitivity scenario

A sensitivity analysis of the ES matrix was applied to test the robustness of the methodological approach. The analysis consisted of the development of a sensitivity scenario based on a four steps method adapted from the five common stages of a scenario development (Metzger et al., 2010). In the first step, the aim of the sensitivity analysis was defined—to test how changes in the scores of ES potential supply of the High-Andean Study matrix affects the results over time. In the second step, two key drivers and their trends that affected (positively or negatively) the potential supply of services were identified from interviews with five experts: climate change and technological improvement of agriculture and forestry.

In stage three, the scenario assumptions were deducted using the trends of the key drivers. These trends were simulated as a rate of positive/negative change (+/− 0.1 per year) on the ES values of the LULC units. Climate change had negative consequences on regulating services supplied by the following ecosystems: natural grasslands, shrublands, forests, glaciers, and high-Andean wetlands. On the contrary, well-managed farming enhanced regulating (erosion, water flow, and soil quality) and provisioning services of agricultural areas and reduced the pollution of rivers and lakes, recovering their functions of purifying water and flow control. Likewise, the technological improvement of forest

plantations increased, regulating services (soil quality, control of soil erosion, water flow, and global climate regulation). The scores of ES for continuous urban fabric and sparsely vegetated areas stayed unaffected.

In stage four, with the simulated scores of ES, two new model matrices for 2009 and 2013 were generated (see Tables A6 and A7 in the Appendix II), whereas, for 2000, that created by the High-Andean Study was used. From these matrices, the ES maps at the four spatial scales were derived running the scaling method defined in Section 2.5. Finally, the assessments of relationships between ES were performed following Section 2.6.2.

3.1. Results for the main objective 1

3.1.1. Changes in the extent of land use/cover categories

Figure 2A shows the spatial distribution of LULC categories across central Moist Puna from 2000 to 2013. The dominant category is natural grassland that is spatially dispersed covering more than 60% of the territory in each year (Fig 2B). The second major LULC type was shrubland, covering more than 15% of the entire area in each year, and mainly located in the south-west it exhibited a transitional zone between the moist Puna and the Peruvian Pacific desert. The third major LULC type was agricultural area with 8% of the landscape in 2000 and top with 12% in 2009, mostly associated to the provinces that form Mantaro watershed. Sparsely vegetated areas and high-Andean wetlands occupied around 6% of the territory each year, covering central and northern areas. Low forest extent reduced from 3% to 1% during the time period, showing a slight aggregation effect with cropland extent. Water bodies and glaciers (only in 2000) represent 1% of the landscape, this last category is spatially associated with sparsely vegetated areas. There were only small amounts of urban lands, forest plantations and water courses covering less than 1% separately.

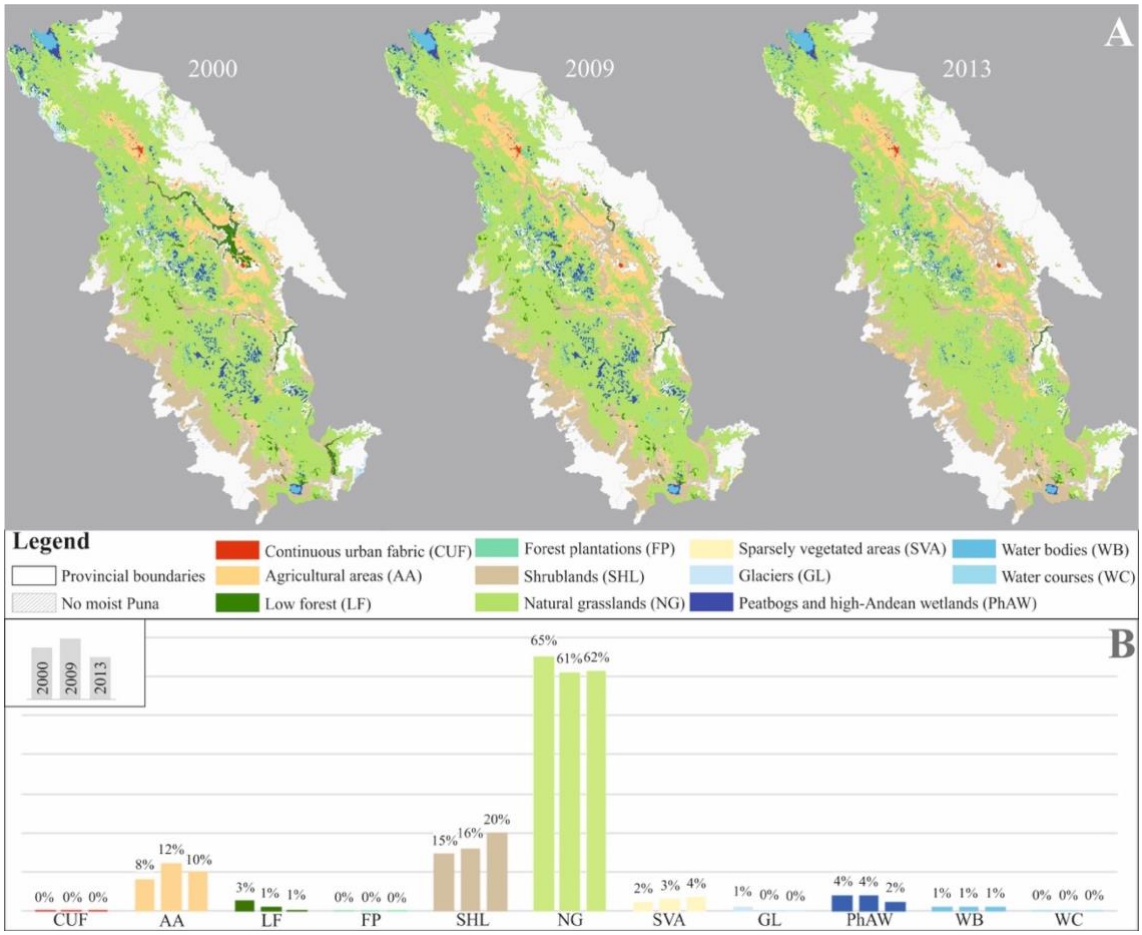


Figure 2: (A) Spatial distribution of land use/cover categories and (B) barplots showing the proportion of land of each category, in central moist Puna across time.

Table 6 presents the transition matrix between 2000 and 2009 in central Moist Puna. The overall agreement (percentage of coinciding area, under equal LULC class) among the comparative maps was 92%. Of the 8% of land-use change, 4.2% disturbed the chosen LULC categories. Agricultural areas increased by about 53.1%, mainly as a result of the encroachment of natural grasslands and shrublands in that order, whereas there was a reduction of 233.6 km^2 after land abandonment. Low forest reduced by 60.2%, being replaced largely by shrublands following a forest degradation process, but forest recovery was also observed (20.8 km^2) due to colonization of shrublands and agricultural land. Natural grasslands decreased by around 2700 km^2, mainly due to expanding agricultural frontier, but their area also slightly increased due to glaciers retreat and dried up of high-Andean wetlands (108 km^2).

2009 / 2000	2.	3.1.1.	3.3.1.	Other	Total	Change (%)*
2.	4881.4	16.3	2400	556.2	**7853.9**	53.1
3.1.1.	10.6	677.5	4.4	10.2	**702.7**	-60.2
3.3.1.	233.6	2.1	38656.9	108	**39000.6**	-6.6
Other	4.3	1069	693.8	14701.2	**16468.3**	7.1
Total	**5129.9**	**1764.9**	**41755.1**	**15375.6**	**64025.5**	

CLC Code: 2. Agricultural areas; 3.1.1. Low forest; 3.3.1. Natural grasslands. * Change ratio between years was calculated as (($Area_i$ in 2009 – $Area_i$ in 2000)/$Area_i$ in 2000) x 100, where $Area_i$ = area of each land use/cover class.

Table 6: Transition matrix showing land-use changes of interest (in square kilometres) and change ratio occurred between 2000 and 2009 in the central Moist Puna

Table 7 introduces the transition matrix between 2009 and 2013 in central Moist Puna. The overall agreement among the comparative maps was 91.8%. Of the 8.2% of land-use change, 2% (1317 km^2) disturbed the chosen LULC categories. Agricultural extent decreased by about 17.7%, mainly as a result of land abandonment (2099.4 km^2), whereas had a growth of 542 km^2 at the expenses of grassland. Low forest (reduced by 47.5%) continued under a degradation process also identified in the preceding time period. Natural grasslands increased by 0.8% (300 km^2) principally by farming de-intensification and the persistent dried up process of high-Andean wetlands.

2013 / 2009	2.	3.1.1.	3.3.1.	Other	Total	Change (%)*
2.	5754.2	8	542.5	160	**6464.7**	-17.7
3.1.1.	0	369.1	0	0	**369.1**	-47.5
3.3.1.	599.4	168.1	37457.8	1081.2	**39306.5**	0.8
Other	1500.3	157.5	1000.3	15221.1	**17885.2**	8.7
Total	**7853.9**	**702.7**	**39000.6**	**16468.3**	**64025.5**	

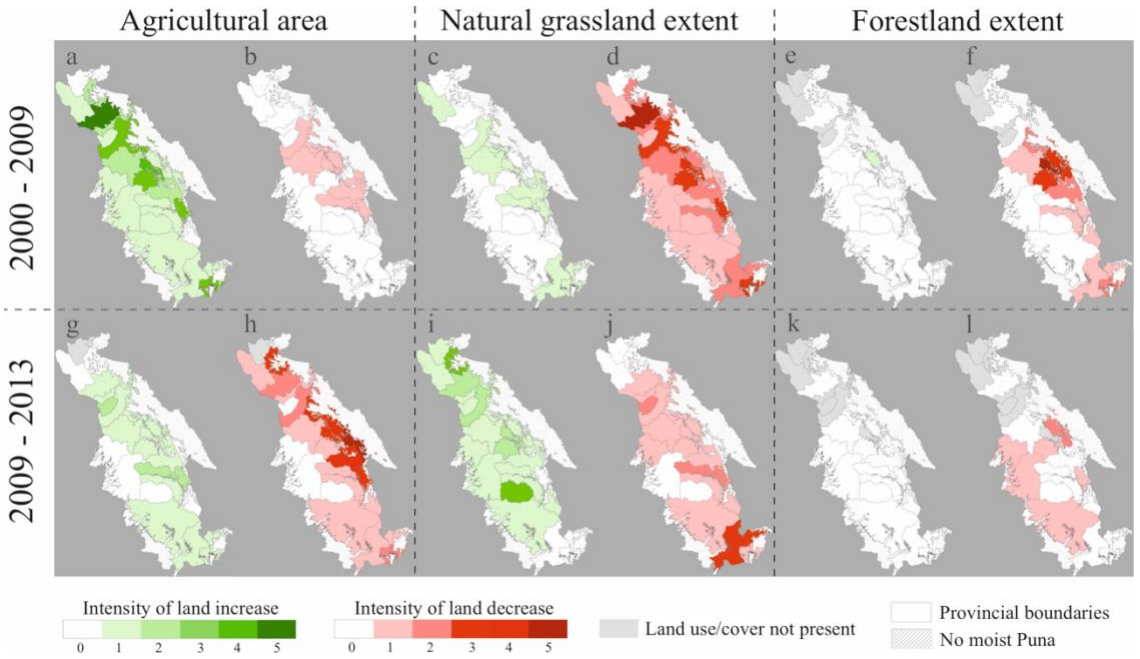
CLC Code: 2. Agricultural areas; 3.1.1. Low forest; 3.3.1. Natural grasslands. * Change ratio between years was calculated as (($Area_i$ in 2013 – $Area_i$ in 2009)/$Area_i$ in 2009) x 100, where $Area_i$ = area of each land use/cover class.

Table 7: Transition matrix showing land-use changes of interest (in square kilometres) and change ratio occurred between 2009 and 2013 in central Moist Puna

Figure 3 on the top row illustrates the intensity of land increase/decrease from 2000 to 2009 across the 25 provinces in central moist Puna. In this initial-time period, central moist Puna described a territory with a tendency to increase cropland areas and to decrease pasture and forestland extents. There are six provinces with a high intensity level and twelve with medium strength level, affected by agricultural area increase, pasture area decrease and forest extent decline. However, most of the provinces had very low proportion of change (32%) or no change (41%) denoting undisturbed areas primarily

related to cropland extent decrease, grassland area increases and forestland extent increase.

At LULC category level, spatial distribution shows that increase in cropland extent (Fig. 3a) was related to decrease in pasture area (Fig 3d), validated by a strong negative correlation (r_p= -0.96839901 and P-value <0.001). In the same way, reduction of agricultural areas (Fig. 3b) corresponded with the expansion of pasture lands (Fig. 3c) proving a negative relationship (r_p= -0.6321261 and P-value <0.001). Forestland extent increase (Fig. 3e) occurred with slight force (1.8% of proportion of land-change) in one province (Churcampa), whereas forest area decreased (Fig. 3f) in 12 provinces (half of the territory), but intensely focussed in four jurisdictions. Pairwise relation between goals and losses of forest class presented a moderate negative correlation (r_p= -0.4194168 and P-value <0.05). Although very slight negative relation was found between forestland decrease and crops increase (r_p= -0.3497234 and P-value <0.1), two strongly deforested provinces (19% for Acobamba and 8.3% for Angaraes) developed an important growth of farming activity (15% for Acobamba and 9.4% for Angaraes).



Ranks of intensity: 0 (no change), 1 (|>0% – 3.8%|), 2 (|>3.8% – 7.6%|), 3 (|>7.6% – 11.4%|), 4 (|>11.4% – 15.2%|), 5 (|>15.2% – 19.0%|)

Figure 3: Land increase/decrease intensity of the chosen land use/cover categories at provincial scale in central Moist Puna.

Figure 3 on the bottom row shows the intensity of land increase/decrease from 2009 to 2013 across the 25 provinces in central moist Puna. In this final-time period, forestland

extent continued declining, grassland extent stayed balanced and agricultural areas decline. Despite these land-use changes, the territory continued, as initial-time period, dominated by areas with very low proportion of change (39% of the provinces) or with no change (33% of the provinces). However, there were strong variations registered in eight provinces due to cropland extent decrease.

At LULC category level, Fig. 3g and Fig. 3j captured similar spatial distribution between provinces affected by cropland extent increase and pasture area decrease, confirming a negative correlation (r_p= -0.5596783 and P-value <0.01). On the contrary, as can be seen from the Fig. 3i and Fig. 3h, enlargement of grassland extent had no significant relation (r_p= -0.0352285 and P-value= 0.8672) with reduction of agricultural areas. Whereas forestland extent declined (Fig. 3l) with very low intensity in seven provinces that were positively interrelated to cropland size decrease (r_p= 0.4883865 and P-value <0.05). It should be noted that no forest area increase was assessed in the final period (Fig. 3k).

3.1.2. Capacity and importance of drivers to predict the distribution of individual land-use changes

Each explanatory variable displayed different spatial distribution within the study area (Fig 4). Population density varied slightly between both periods, characterizing a territory with eleven provinces in a growing rate and fifteen provinces with a declining proportion over time. Income driver showed rather similar values for all the provinces, except for three provinces, Huamanga and Huancayo that include a major city each, and Yauli characterized by mining development. Education presented provinces of Junin with a higher percentage of people with completed secondary school than the provinces of Ayacucho and Huancavelica.

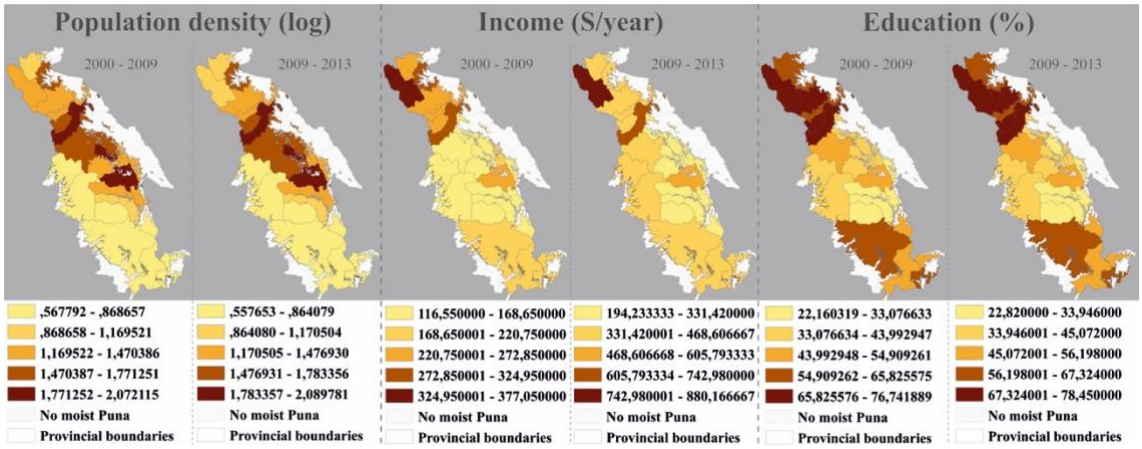
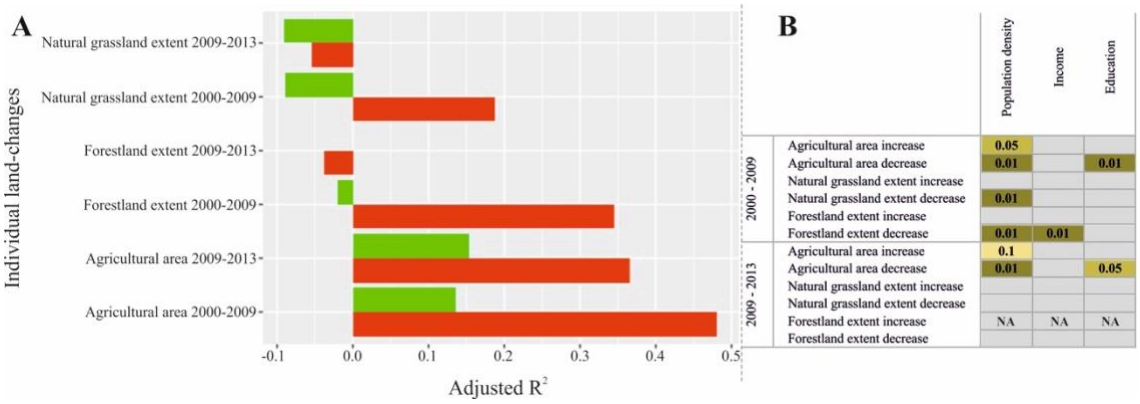


Figure 4: Spatial distribution of each driver for both time periods. The values of drivers are organized in equal interval quintiles.

There were disparities regarding how well the drivers predicted individual land-use changes (Fig. 5A). Changes in area decrease were better predicted in agricultural area (both periods), forestland extent (2000-2009) and natural grassland extent (2000-2009), in that order. Natural grassland decrease (2009-2013), forestland extent decrease (2009-2013) and all changes in area increase were poorly predicted by all three drivers. Overall, our results show that variations of cropland extent were the best explained.

The function "ordistep" of redundancy analysis showed that the significance to predict land-use changes was shared among variables, and that different land-use changes were best predicted by different variables (Fig. 5B). Population density was the best driver for predicting cropland area changes (both periods), forestland and pasture extent decrease (2000-2009). Income did well predict forestland extent decrease during 2000-2009, and education did well explain agricultural area decrease in both time-steps. No variables predicted natural grassland decrease (2009-2013) and increase (both periods), forestland extent decrease (2009-2013) and increase (2000-2009). Overall, drivers had best significance clarifying changes in the first-time period.



Boxes with P-value of significant relationship are coloured; darker colours indicate a strong correlation; grey boxes indicate no significance; NA indicates not available.

Figure 5: (A) Capacity of drivers to predict the distribution of individual land-use changes for the two-time periods using RDA (green horizontal barplots are related to LULC area increase; red horizontal barplots are relate to LULC area decrease) (B) Importance of each driver (Population density, Income, Education) for predicting individual land-changes for the two-time periods

3.2. Results for the main objective 2

3.2.1. Land-change dynamics

Twenty-two (during de period 2000-2009) and twenty-four (during de period 2009-2013) types of transitions were assessed and grouped in six land-change dynamics (Table 8). Agricultural expansion (D1) was the more extensive land-change dynamic in the initial time-period (T1), implicating the conversion of low forest, shrublands and natural grasslands. Agricultural de-intensification (D2) represented an increase of grasslands and shrublands due to fallowing and/or land abandonment, largely registered during the second time-period (T2). Deforestation (D3) of low forest gave way to shrublands and natural grasslands, increased during T1 and decreased during T2. Dynamic type 4 represented by urbanization showed that urban areas slightly augmented by the encroachment of natural grasslands and agricultural areas. Afforestation (D5) of pine and eucalyptus species had a higher increase during T1, whereas in the second time-period showed a slight growth. Natural processes (land-change dynamic type 6) set diverse type of changes during T1, highlighting the reduction of nival zones (−66.78%) and boosting the expansion of sparsely vegetated areas. While during T2, there were important transitions registered as the extensive reduction of peatbogs and high-Andean wetlands increasing natural grasslands.

Code	Land-change dynamic	Type of change	2000 – 2009 (T1)		2009 – 2013 (T2)	
			Km^2	%	Km^2	%
D1	Agricultural expansion	LF to AA	16.3	0.3	8.1	0.15
		SHL to AA	556	9.8	133.2	2.44
		NG to AA	2400	42.3	542	9.92
		PWL to AA	0	0	24.9	0.46
D2	Agricultural de-intensification	AA to NG	233.6	4.1	599.4	11
		AA to SHL	0	0.0	1492.7	27.3
D3	Deforestation	LF to NG	2.1	0.04	168	3.1
		LF to SHL	1068.8	18.8	157.4	2.8
D4	Urbanization	NG to CUF	0	0	3.8	0.1
		AA to CUF	0	0	7.6	0.1
D5	Afforestation	NG to FP	96.7	1.7	10	0.2
		AA to FP	4.1	0.1	0	0
		SHL to FP	10.5	0.2	0	0
D6	Natural processes	Miscellaneous	1288	22.7	2313.8	42.4
		Total	5676	100	5461	100

LULC classes and abbreviations: Continuous urban fabric (CUF), Agricultural areas (AA), Low forest (LF), Forest plantations (FP), Natural grasslands (NG), Shrublands (SHL) and Water courses (WC).

Table 8: Estimated area (km^2) of each type of changes and land-change dynamics occurred from 2000 to 2013 in the study area.

3.2.2. Ecosystem services potential supply matrix

The expert scores for regulating ES and the results of the standardized method for provisioning ES are presented in Fig 6A. The details of the quantity of consulting experts, the outliers identified and the contributing answers for each LULC/regulating ES pairs are systematized in (Table A3 Appendix II).

Peatbogs and high-Andean wetlands afforded the highest potential supply for both ES sections. Low forest, natural grasslands and shrublands got higher values for regulating ES. Glaciers and water bodies had very high potential supply of regulating water flow. Water bodies and water courses got high performance purifying water, whereas forest plantations highlighted by its soil erosion control and carbon sequestration. Agricultural areas presented low and medium supply for crops and livestock services, respectively. Finally, continuous urban fabric and sparsely vegetated areas are related with no relevant provision in almost all the ES.

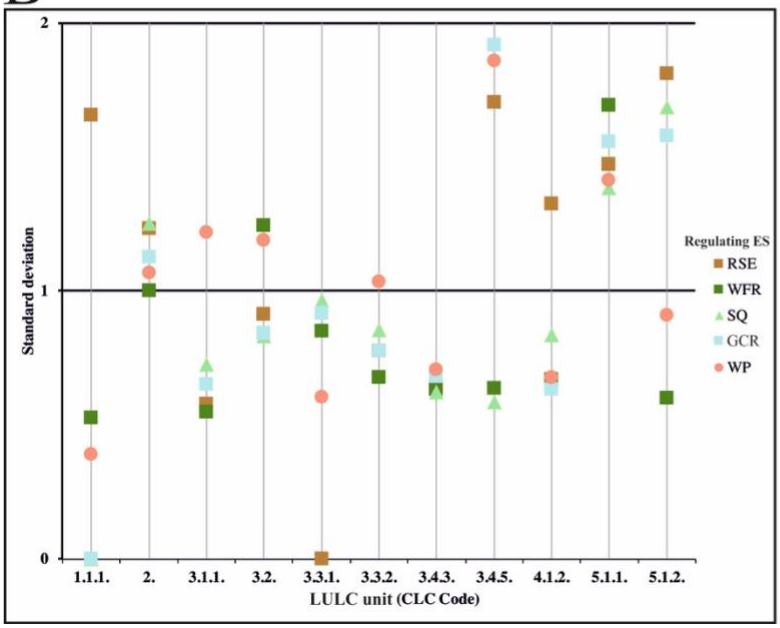
A

Scale for assessing potential supply

0.00 - 0.83	no relevant potential supply
>0.83 - 1.67	very low potential supply
>1.67 - 2.50	low potential supply
>2.50 - 3.34	medium potential supply
>3.34 - 4.17	high potential supply
>4.17 - 5.00	very high potential supply

		Regulating ES					Provisioning ES	
CLC Code	LULC unit	Water purification (WP)	Regulation of soil erosion (RSE)	Water flow regulation (WFR)	Soil quality (SQ)	Global climate regulation (GCR)	Crops (CR)	Livestock (LS)
1.1.1.	Continuous urban fabric	0.18	1.21	0.32	0.00	0.00	0.00	0.00
2.	Agricultural areas	1.50	1.84	2.65	2.26	2.00	2.03	2.61
3.1.1.	Low forest	3.69	4.33	4.27	4.13	4.32	1.56	1.93
3.2.	Forest plantations	2.71	3.63	2.95	2.69	3.89	1.54	2.03
3.3.1.	Natural grasslands	3.55	4.00	3.76	3.70	3.37	1.49	2.18
3.3.2.	Shrublands	3.45	3.92	3.83	3.80	3.68	1.53	1.73
3.4.3.	Sparsely vegetated areas	0.75	0.50	0.75	0.68	0.61	1.20	1.58
3.4.5.	Glaciers	1.83	1.35	4.56	0.33	1.66	0.00	0.00
4.1.2.	Peatbogs and high-Andean wetlands	4.54	3.91	4.53	4.29	4.55	2.10	3.49
5.1.1.	Water courses	3.28	1.29	3.12	1.20	1.72	0.00	0.00
5.1.2.	Water bodies	3.75	1.52	4.54	1.45	2.74	0.00	0.00

B



C

	Regulating ES					
CLC Code	WP	RSE	WFR	SQ	GCR	
1.1.1.	0.24	1.46	0.41	0.00	0.00	ES Sensitivity Matrix 1: Expert scores + SE
2.	1.66	2.03	2.81	2.45	2.17	
3.1.1.	3.88	4.42	4.36	4.24	4.42	
3.2.	2.90	3.78	3.14	2.83	4.03	
3.3.1.	3.65	4.00	3.89	3.85	3.51	
3.3.2.	3.62	4.04	3.94	3.93	3.81	
3.4.3.	0.86	0.60	0.85	0.78	0.72	
3.4.5.	2.12	1.62	4.66	0.43	1.96	
4.1.2.	4.65	4.11	4.63	4.42	4.65	
5.1.1.	3.50	1.52	3.38	1.42	1.97	
5.1.2.	3.90	1.80	4.64	1.71	2.98	
1.1.1.	0.12	0.96	0.23	0.00	0.00	ES Sensitivity Matrix 2: Expert scores - SE
2.	1.34	1.65	2.49	2.07	1.83	
3.1.1.	3.50	4.24	4.18	4.02	4.22	
3.2.	2.52	3.48	2.76	2.55	3.75	
3.3.1.	3.45	4.00	3.63	3.55	3.23	
3.3.2.	3.28	3.80	3.72	3.67	3.55	
3.4.3.	0.64	0.40	0.65	0.58	0.50	
3.4.5.	1.54	1.08	4.46	0.23	1.36	
4.1.2.	4.43	3.71	4.43	4.16	4.45	
5.1.1.	3.06	1.06	2.86	0.98	1.47	
5.1.2.	3.60	1.24	4.44	1.19	2.50	

(A) The matrix illustrates the flow of regulating and provisioning ES potential supply in the moist Puna. (B) The graph displays the standard deviation for expert responses in each LULC/regulating ES pairs. (C) The ES sensitivity matrix 1 shows the expert scores plus the standard error. The ES sensitivity matrix 2 presents the expert scores minus the standard error. The cells with red outline denote a one-level class variation in the potential supply.

Figure 6: ES matrix (A) and descriptive statistics for the sensitivity analysis (B and C).

3.2.3. Sensitivity analysis of the capacity matrix

A sensitivity analysis was carried out to evaluate the variability and the uncertainty in the regulating ES matrix scores. The variability of the expert responses had a low

significance, varying between SD=0 for agreements and up to SD=1.918 for the biggest discrepancies (Fig 6B). The results showed that 5% of the scores got an unanimous response, while 55% had very low variability. Glaciers and water bodies gathered the higher SD values with global climate change and regulation of soil erosion services, respectively. Although, water purification was the service that accumulated more percentage of discrepancies (11%), showing low reliability. Whereas, water flow regulation and soil quality services grouped 15% of low variability responses.

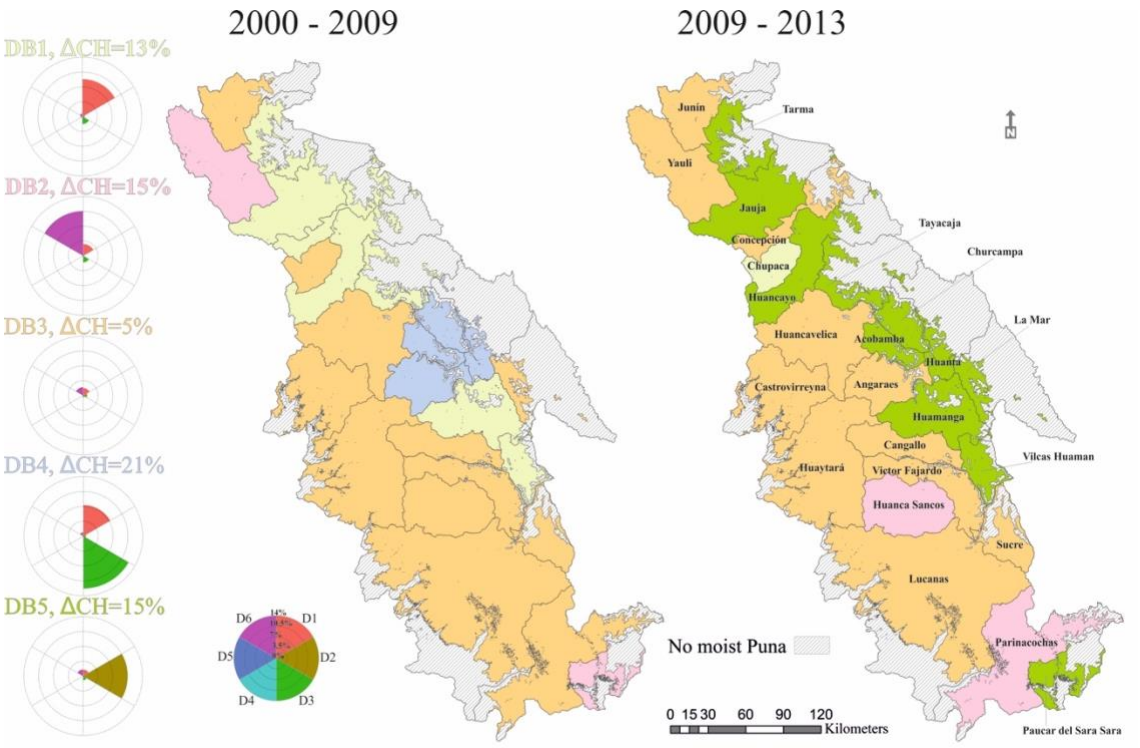
The comparison between the sensitivity matrices 1 and 2 (Fig 6C) and the regulating ES matrix indicated 87% and 84% of overall agreement of cells under equal class of the potential supply, respectively. The minor differences supposed an increment or decrement one level in the potential supply scale in 7 and 9 expert scores after adding or deducting the SE value as it should. Kappa coefficient for the sensitivity matrices 1 and 2 were 0.84 and 0.79 representing "almost perfect" and "substantial" accuracy. By LULC, continuous urban fabric and forest plantation continued undisturbed after submitting the changes. Sparsely vegetated areas and water bodies have the largest potential increment, while agricultural areas and water courses show the biggest supplying reduction. By regulating ES, water flow regulation and soil quality services were the most augmented, quite the opposite occurred with water purification and global climate regulation services. In summary, the low variability of the responses and stability around the mean values signified robustness of the regulating ES matrix scores for the studied area.

3.2.4. Cluster analysis for land-change dynamics

The provinces were grouped into five types of clusters based on the kind and proportion of land-change dynamics occurred through time (Fig 7). The bundle type 1 (ΔCH=13%), grouped eight provinces (seven in T1 and one in T2) with a dominant process of agricultural expansion following by a slight reduction of low forest. Two provinces in each time-period (cluster DB2, ΔCH=15%) were mainly controlled by natural processes, highlighting glaciers retreat (during T1) and reduction of peatbogs and high-Andean wetlands in the final period. The third bunch (DB3) included the provinces practically undisturbed (12 provinces for 2000-2009 and 11 provinces for 2009-2013). Whereas, group type 4 (DB4), displayed four provinces that experienced the largest LULC changes (ΔCH=21%), due to deforestation and agricultural expansion, during the initial time-period. The fifth bundle (DB5, ΔCH=15%) grouped eleven provinces by their agricultural

de-intensification in the final time-period. It should be noted that urbanization (D5) and afforestation (D6) had very short percentage of changed land, graphically imperceptible in each star plot (Fig 7).

DB3 (lowest land-change trend) is the cluster with the larger number of provinces in the two-time periods, representing 48% and 44% of provinces respectively. From this group, eight provinces (32%) kept unalterable trends through time. Despite this uniformity, there were nine different changes followed by these provinces (see Fig A8A in the Appendix II). Three principal types of variations described the 65% of all the changes. Six DB1 and three DB4 provinces changed to become DB5 showing a clear trajectory of agricultural abandonment. Two provinces DB3 (Parinacochas and Huanca Sancos) changed to DB2 due to enlargement of shrublands and drying of peatbogs and high-Andean wetlands correspondingly.

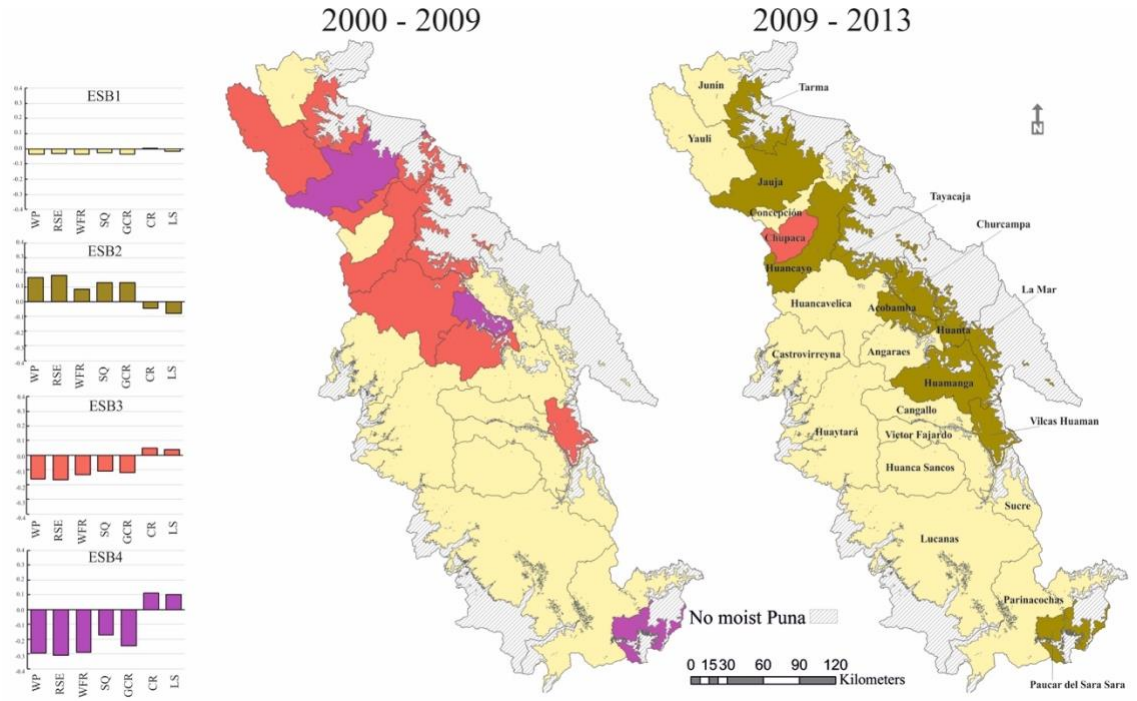


Star plots illustrate the land-change dynamics and the total percentage of transformed land (ΔCH) for each cluster. Each ray length is proportional to the percentage of changed land of its corresponding dynamic (rays are comparable within clusters). Land-change dynamic types and abbreviations: agricultural expansion (D1), agricultural de-intensification (D2), deforestation (D3), urbanization (D4), afforestation (D5) and natural processes (D6).

Figure 7: Clusters of land-change dynamics spatially distributed over the two-time periods.

3.2.5. Bundles of ES trends and relationships among individual ES trends

Cluster analysis defined four groups based on ES potential average trends of each province boundary over time (Fig 8). The bundle type 1, ESB1 revealed that twenty-seven provinces (fourteen in T1 and thirteen in T2) had a slight loss in regulating services and a constant supply of provisioning services over time. Eleven provinces (Bundle ESB2) experienced an improvement of regulating services and a reduction of provisioning in the final time period. The positive changes occurred under a trend of land abandonment and fallowing. Bundle ESB3 showed provinces (primarily in T1) with an overall change that had negative effects on regulating services. The fourth bundle (ESB4) included three provinces that enlarged their potential of provisioning services and highly reduced regulating services.



Barplots show the ES potential average variation within each bundle type. Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS).

Figure 8: Spatial distribution of ecosystem service bundles (ESB) grouping the ES potential average trends over the two-time periods.

Nine ESB1 provinces formed a large cluster with low variability in ES provision reflecting low changes in the landscape through time. Sixteen provinces changed their bundles over time defining mainly four different paths (Fig A8B in the Appendix II). Thirty percent of provinces providing ESB1 (low trend of ES supply) in T1 changed to ESB2 (increasing trend of regulating ES and decreasing trend of provisioning ES) by the final time period, reflecting a tendency of agricultural abandonment. Provinces

characterized by a strong negative trend in regulating services (ESB4) in the initial time period changed to ESB2 in T2, showing the recovery of ecosystems. Ninety percent of ESB3 provinces changed equally to ESB2 or ESB1 by T2, displaying a landscape with a positive trend in regulating ES. Only one province (Chupaca) increased provisioning services supply (ESB3) as a detriment of regulating ES.

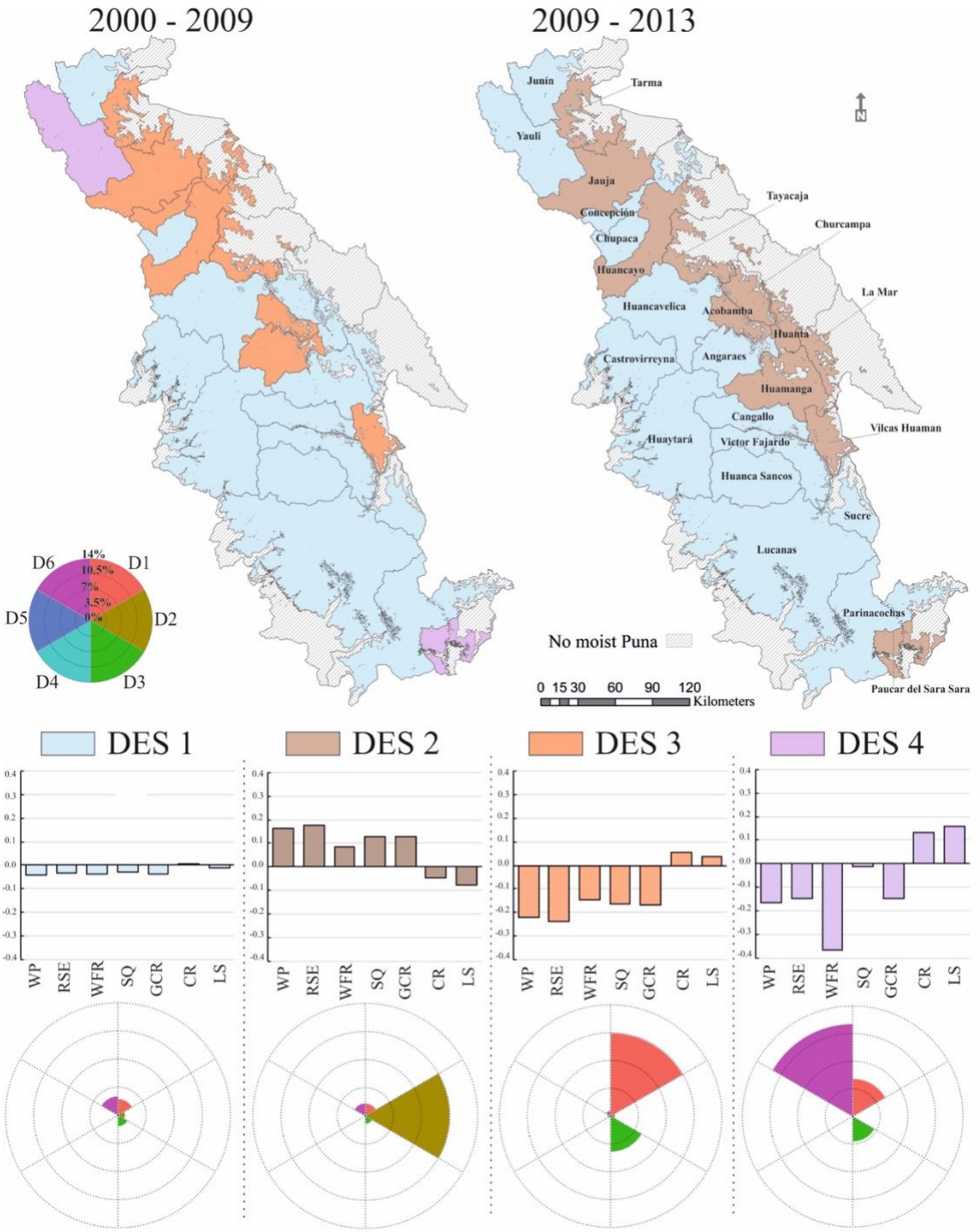
At phytoregion scale, the type and strength of the interactions among ES trends over the two-time periods are detailed in Table A9 (Appendix II). Regulating services correlations were strongly positive through time. Trade-offs appeared with high strength among provisioning and regulating services for both time periods, only soil quality had a not significant negative relationship with livestock during the initial time-period. Crops and livestock services had a strong positive correlation through time. Twenty interactions for initial time period were significantly ($p < 0.05$), whereas each interaction for T2 were significant.

3.2.6. Associations between clusters of land-change dynamics and ecosystem service trends

Overlap and cluster analysis defined four links between land-change dynamics and ES trends (Fig 9). The first link (DES1, ΔCH=7%) is the largest in both time periods, grouping 30% and 28% of provinces respectively, mainly connecting ESB1 and DB3 clusters (80% of the connections in the group). This cluster showed a territory with a slight decrease in regulating services and minor variation of provisioning services, including provinces (Junin, Huaytara and Castrovirreyna) with a land-change proportion lower than 3% for both time periods. However, there were two provinces in T1 (Huanta and Churcampa, association ESB1 and DB4) with higher change proportion (12% and 19%) dominated by deforestation (70 % of the strength for both provinces). Also, one province ESB1 and DB1 (Huamanga, ΔCH=14%) was marked by a growth of farming and deforestation in T1.

Group DES2 (clusters DB5 with ESB2) defined eleven provinces in the final-time period (44% of the territory) with 15% of transforming land, characterizing areas by agricultural de-intensification (71% of the strength), that increased regulating services supply and decreased provisioning ES. In this link the two provinces (Huanta and Churcampa) that gathered the highest land-change proportion (23% and 22% respectively) also experienced a severe deforestation process (42 and 50 km^2 correspondingly).

The third link (DES3) is composed principally by DB1 and ESB3 provinces, describing eight provinces in the initial-time period that produced a high land-change proportion (ΔCH=17%), primarily due to agricultural expansion and deforestation (60 % and 27% of the total average change calculated by this link respectively). These changes produced positive effects on provisioning services at the expense of regulating ES. It should be noted that a province (Acobamba, ESB4 and DB4) had the largest individual land-change (36%), resulting in 15% of agriculture extension and 19% of forest decline in its territory. Two provinces formed the fourth association (DES4) characterised by a positive supply of provisioning services and negative trend of regulating ES (ESB3 and ESB4) obtained with a land-change average of 20% during the first-time period. Both provinces are determined by bundle DB2 highly induced by natural processes (60% of the total average change calculated by this link), that affected negatively water flow regulation. It should be noted that increase of crops and livestock potential were a consequence of glaciers retreat and expanding agricultural frontier.



Star plot and barplot describes each link between clusters of land-change dynamics and ecosystem service trends. Star plots illustrate the land-change dynamics and the total percentage of transformed land occurred in each cluster. Each ray length is proportional to the percentage of changed land of its corresponding dynamic (rays are comparable within clusters). Barplots show the ES potential variation within each bundle. Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS). Land-change dynamic types and abbreviations: agricultural expansion (D1), agricultural de-intensification (D2), deforestation (D3), urbanization (D4), afforestation (D5) and natural processes (D6).

Figure 9: Spatial distribution of links over the two-time periods.

The spatial distribution of associations between clusters of land-change dynamics and ecosystem service trends changed through time. Although DES1 (slight land-changes and minor ES variations) was the dominant link in both time periods, making a large group

of eleven provinces, there were three relevant variations followed by the remaining fourteen provinces (Fig A8C Appendix II). Six provinces defined by link DES3 (crops and livestock expansion), one DES4 province (crops, livestock and water flow regulation fall) and four DES1 provinces changed to DES2 (regulating services), reflecting tendencies toward crop production specialization following agricultural de-intensification. Two provinces DES3 and one province DES4 also changed to enlarge DES1 cluster.

At regional scale, the development occurred in the initial-time period displayed a territory influenced by land-change dynamics that caused an improvement of crops and livestock provision, largely due to agricultural expansion. This condition, together with natural processes and deforestation generated negative effects on regulating service provision. Whereas, the final-time period showed a landscape with a increasing trend in regulating ES, where land abandonment was the dominant land-change dynamic.

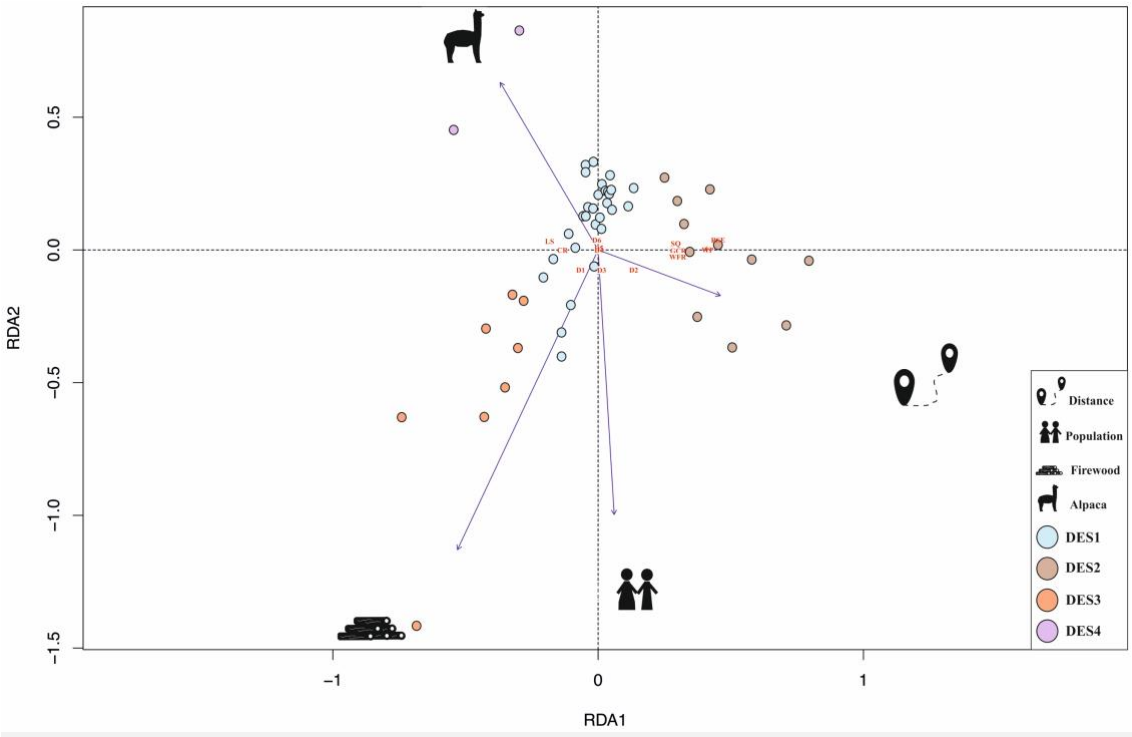
The redundancy analysis (RDA) revealed the important land-change dynamics for predicting the variability of ES within each province over the two time periods. Both land-change models had a high capacity to explain the performance of ES (Model T1: R^2=0.949 and P-value <0.001; Model T2: R^2=0.952 and P-value <0.001). In order to their partial contribution, the significant dynamics for model T1 were agricultural expansion, natural processes, deforestation and agricultural de-intensification. Whereas for model T2 were agricultural de-intensification, agricultural expansion and natural processes. Afforestation and urbanization had insignificant influence in the distribution of individual services in both models, whereas deforestation was irrelevant for model T2. Results of RDA analysis are in Table A10 (Appendix II).

3.2.7. Explanatory variables for land-change dynamics and ecosystem services

The RDA specified firewood, population, alpaca and distance from Lima as the relevant variables that best explicated the two-time models generated by land-change dynamics and ES trends, R^2=0.36 and P-value <0.001. Each explanatory variable displayed different spatial distribution within the study area (Fig A11 in Appendix II). Firewood consumption showed higher values in the initial time period in all the provinces. In contrast, the density of alpacas presented an increment in almost each province during the second-time period. Population density varied slightly between both periods, characterizing a territory with eleven provinces in a growing rate and fifteen provinces

with a declining proportion over time. Distance from Lima showed that most of the provinces are situated beyond four hundred kilometers.

The plot (scaling 2) of the RDA results for land-change dynamics and ES trends across the moist Puna is shown in Fig 10. Most of the provinces with very low changes in ES provision and land (DES1) were remote from Lima, had a low population density, a growing alpaca activity and low firewood consumption. Provinces that experience an increase of regulating services and a reduction of provisioning (DES2) during the final time period were related to areas with low alpaca density, high population density and middle-low distance to Lima. Provinces with an augmentation of provisioning services (DES3) and reduction in regulation services during the first-time period stayed in areas with high population density and growing fuel wood needs. The two provinces (DES4) during the initial time period had medium consume of firewood, high expansion of alpaca breeding and low-medium population density.



The plot shows the constrain of the drivers (blue), the unconstrained dynamics and ES (red) and the association bundles (coloured points). Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS). Dynamic types and abbreviations: agricultural expansion (D1), agricultural de-intensification (D2), deforestation (D3), urbanization (D4), afforestation (D5) and natural processes (D6). Drawings were generated with CorelDRAW X7.

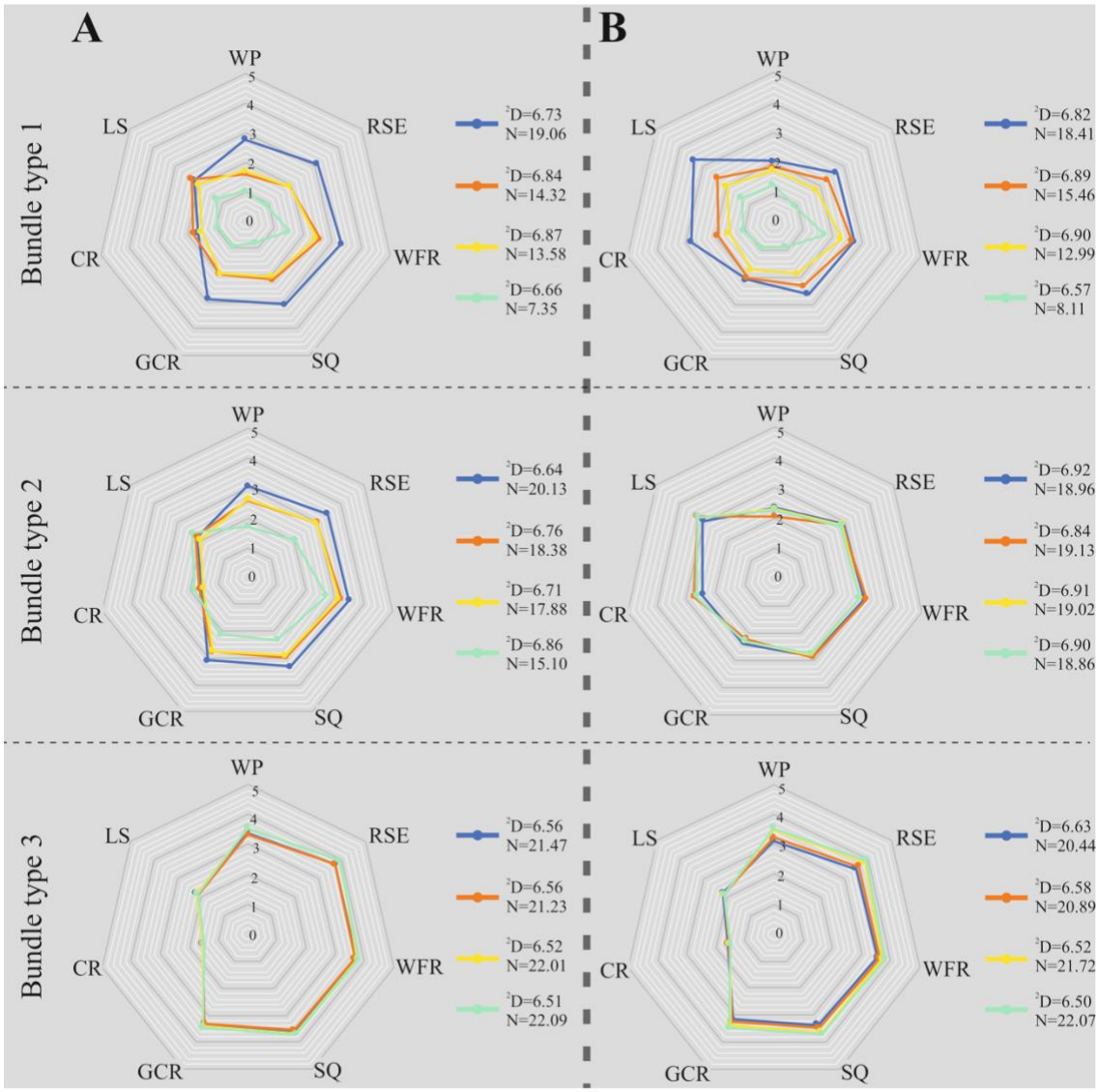
Figure 10: Redundancy analysis results across the moist Puna.

3.3. Results for the main objective 3

3.3.1. Static Cluster Analysis

The results of the two metrics used to evaluate the effects of the four spatial scales on the configuration of bundles showed similarities and disparities (Fig 11A). Regarding similarities, all the bundles provided an effective number of ES that ranged from 6.51 to 6.87. Concerning dissimilarities, most of the bundle types indicated disproportions among the abundance of ES. However, it showed a trend towards being higher for larger spatial scales. Additionally, there was a trend of increasing of ES abundance from bundle type 1 to type 3 at each spatial resolution, but it had more similarities when the spatial scale increased. In that way, the provincial level was defined by the slight variation of ES values of the three bundle types. However, at the municipal level, type 3 was a multifunctional bundle, type 2 was a multifunctional agricultural bundle, and type 1 corresponded to an agriculture bundle. The coarse-grid scale mainly differed from the municipal in the bundle type 1 (agriculture and sparsely vegetated areas). However, at the fine-grid, the ES bundling showed a multifunctional bundle (type 3), an agriculture bundle (type 2), and an urban and sparsely vegetated area bundle (type 1).

The sensitivity analysis showed similarities between the effective number of ES provided by all the bundles, whereas the highest differences were detected among the abundance of bundles (Fig 11B). The diversity and the abundance of ES provided in bundles type 3 and type 2 was similar at the four scales of observation, whereas in type 1, differed. Thus, type 3 was a bundle with the highest values of regulating services, and type 2 was a bundle with the highest values in crop and livestock services. However, type 1 at the provincial level kept similarities with type 2, whereas at the municipal and grid scales had the lowest values of ES defined by urban and sparsely vegetated areas.

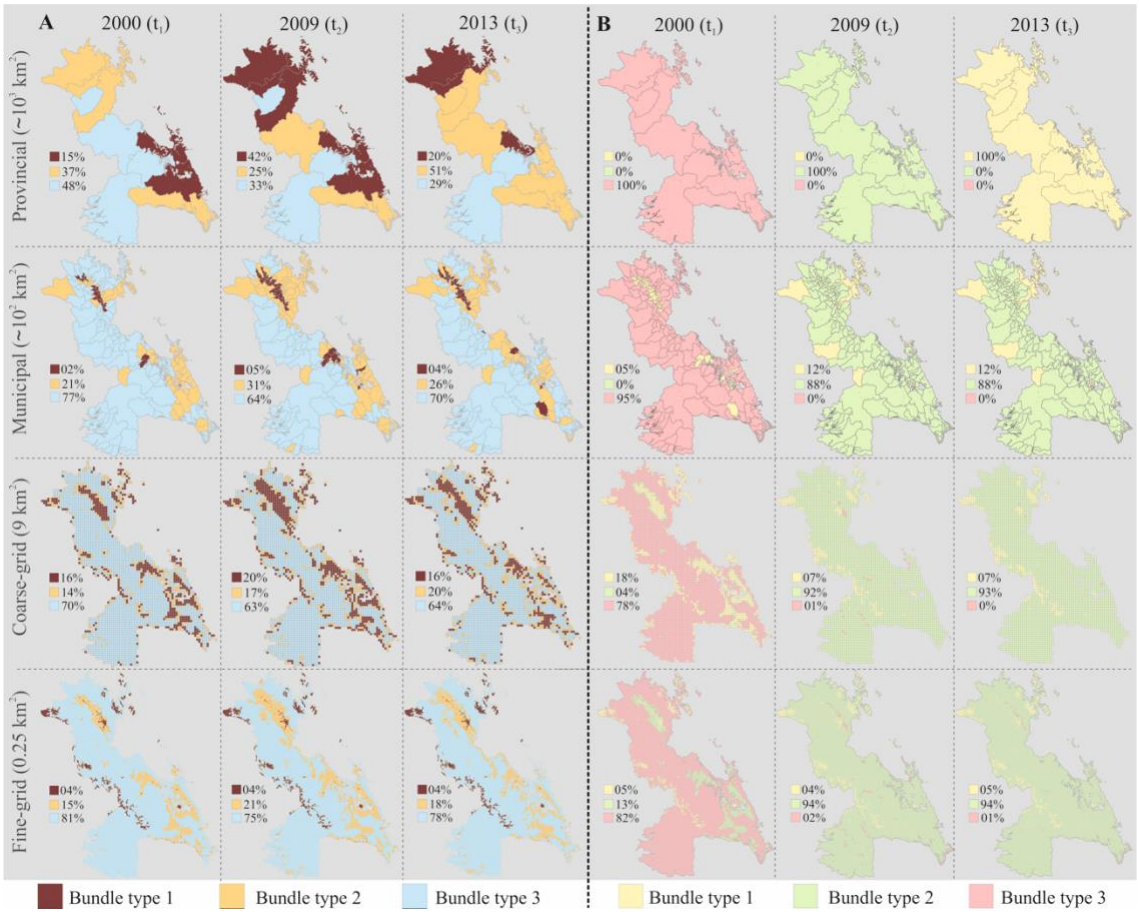


Spider charts illustrate the abundance of ES potential supplied by each bundle. Each axe length is proportional to the relative abundances of the other ES within each bundle (axes are comparable within bundles). Metrics and abbreviations: true diversity (^2D), and abundance (N).

Figure 11: Configuration of bundles and metrics derived from ES values (A) and the sensitivity analysis (B) at the four spatial scales.

The spatial distribution of bundles obtained from ES values showed higher similarities among the three smaller spatial scales (Fig 12A). Thus, bundle type 3 dominated the territory (percentage of land >63%) over the three years. Nevertheless, the agricultural bundle had higher correspondences between grid-scales. At the provincial level, the three types of bundles were more evenly distributed (Fig 12A). The sensitivity analysis showed that the similarities between the spatial distribution of bundles followed a trend towards being higher for small spatial scales (Fig 12B). Then, at the municipal level and the two grid-scales, bundles kept fair spatial consistency across time, especially for types 2 and

3. On the contrary, at the provincial level, the territory was defined by a bundle type each year.



Maps show the spatial distribution and proportion of land of each bundle over time and across each spatial scale.

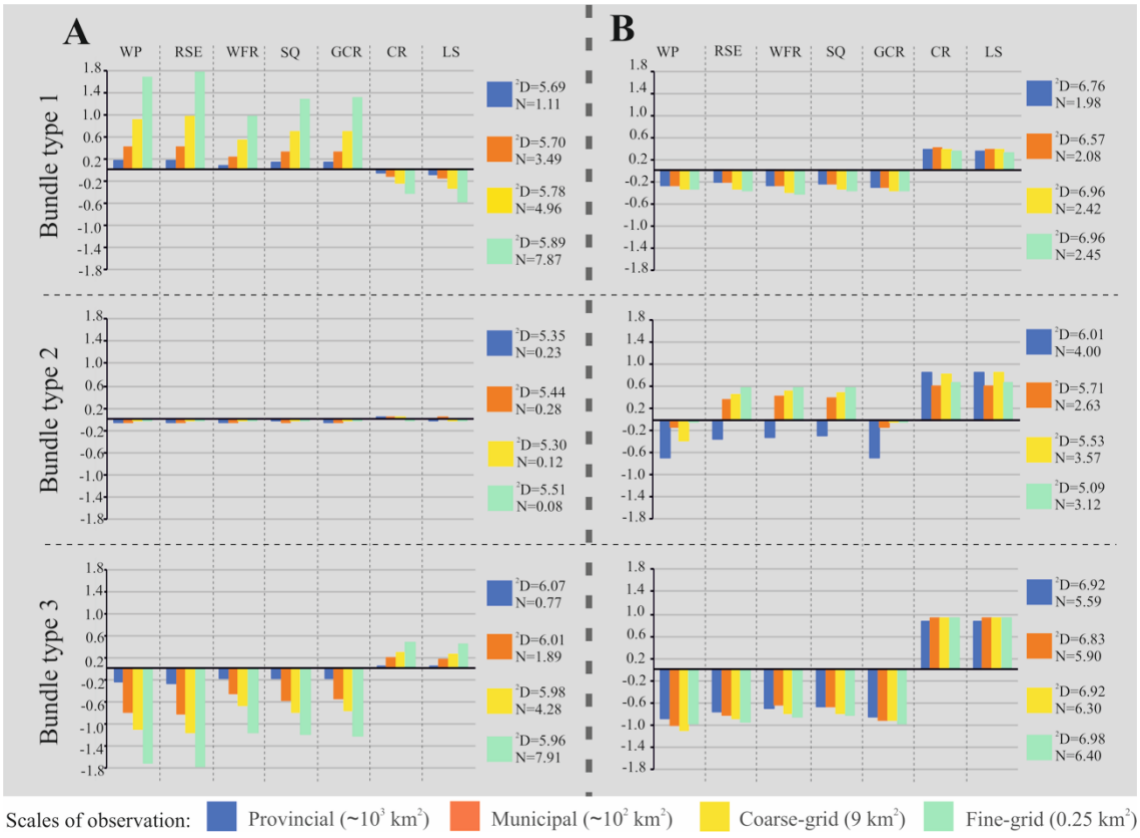
Figure 12: Spatial distribution of bundles resulting from ES values (A) and the sensitivity analysis (B) across the four spatial scales over the three years.

The analysis of historical trajectories showed that the bundle provided by any given land changed through time at each spatial scale but followed a decreasing trend from large to small (Table A12, Appendix II). During the total study period, at the provincial level, 68% followed any trajectory of change, whereas this change was 30% at the municipal level. In the same way, the coarse-grid and fine-grid showed inferior variations of 24% and 14%, respectively. Furthermore, there was a second trend towards a higher number of transitions for fine spatial scales. These two trends were confirmed by the sensitivity analysis (Table A13, Appendix II).

3.3.2. Dynamic Cluster Analysis

The analysis of the configuration of bundles at the four spatial scales presented similar measures of the effective number of ES changes (that ranged from 5.30 to 6.07), but differences in most of the N values (Fig 13A). Only bundle type 2 did not manifest these dissimilarities, since describing a territory without land-use change at the four spatial resolutions, remaining with similar and lowest N (almost 0). On the contrary, the N values specified by bundles type 1 and type 3 decreased when the spatial scale increased. In this regard, bundle type 1 revealed an increasing pattern from larger to smaller spatial scales, that detected the reduction in regulating services, and the increase in provisioning ES. However, bundle type 3 specified a trend of increase in provisioning services and a decrease in regulating.

For the sensitivity analysis, Fig 13B shows the similarities and the differences between the configuration of bundles across the four spatial scales. Similarities of the 2D metric are found for types 1 and 3, whereas type 2 showed higher differences across the four spatial scales. On the other hand, the N metric showed that for each bundle type, grid-scales had higher similarities between them and the municipality level. Furthermore, bundles type 1 and type 3 showed a consistent configuration of positive values of provisioning services and negative of regulating, whereas type 2 differed at the provincial level in the regulating services. Thus, bundles showed higher similarities among the three smaller spatial scales.



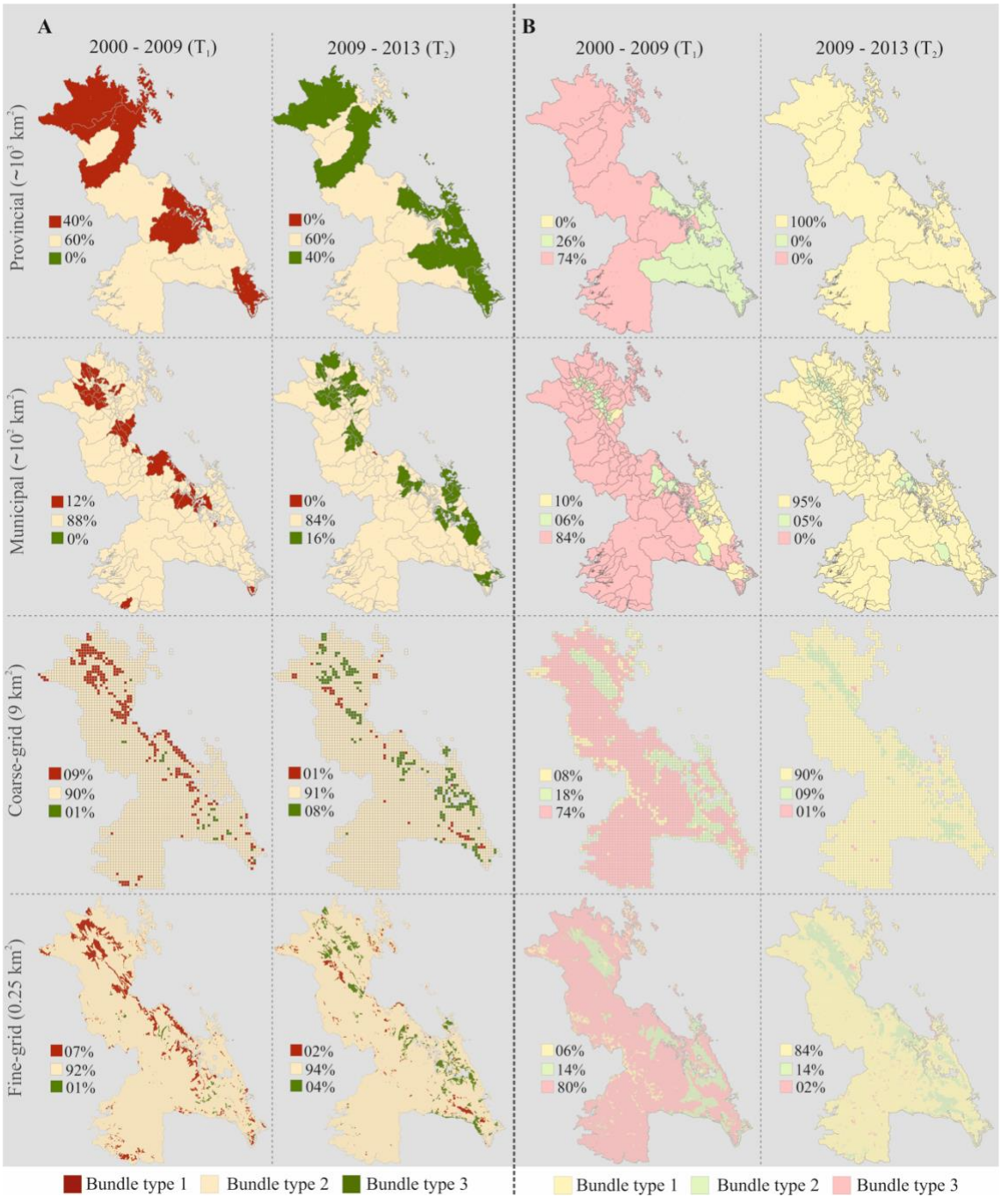
Bar plots show the amount of change in ES values at two times within each bundle type. Each bar length is proportional to the relative abundances of the other ΔES values within each bundle (bars are comparable within bundles). Metrics and abbreviations: true diversity (2D), and abundance (N).

Figure 13: Configuration of bundles and metrics derived from ΔES values (A) and the sensitivity analysis (B) at the four spatial scales.

The spatial distribution of bundles across the two smaller spatial scales displayed a consistent pattern that began to be less evident at the provincial level (Fig 14A). In that sense, at the municipal level and on the two grid-scales, the territory seemed dominated by bundle type 2 (percentage of land >84%), whereas this percentage strongly declined at the provincial level. Likewise, the sensitivity analysis indicated fair robustness between municipal and grid-scales (Fig 14B). However, there were minor areas with changes in ES supply only detected at grid resolutions.

Historical trajectories of bundles achieved with ΔES values showed that the land that changed from one to another differed among spatial scales but was higher (52%) at the provincial level than at smaller levels (municipal: 24%; coarse-grid: 16%; fine-grid: 13%) (Table A14, Appendix II). These transitions uncovered four main trajectories at all the spatial scales, and two more only found at the grid scales. Likewise, the sensitivity analysis showed that the proportion of land changing from one bundle to another was

higher at the provincial level, and the number of trajectories was higher as the spatial scale decreased (Table A15, Appendix II).



Maps show the spatial distribution and proportion of land of each bundle over the two-time periods and across each spatial scale

Figure 14: Spatial distribution of bundles resulting from ΔES values (A) and the sensitivity analysis (B) across the four spatial scales at each period.

CHAPTER 4. DISCUSSION

4.1. Understanding land-use changes in the central high-Andean moist Puna

This study analyzed spatial patterns of land-use change occasioned by human activities in central high-Andean moist Puna since 2000. The results described three patterns: (1) a North – South division in terms of land-use change intensity over time, (2) two spatially different trends of intensifying agriculture during 2000-2009 and de-intensification during 2009-2013, negatively correlated to natural grassland extent, and (3) a persistent negative trend of forestland area over time and across space. Moreover, the observed land-use change trends were predicted by explanatory variables based on publicly available data.

The first spatial pattern identified a North - South division in terms of land-use change intensity that was primarily related to population growth factor (Figures 4 and 5B). Northern side of the moist Puna was characterized by high intensity levels of land increase/decrease in each chosen LULC type (Fig 3). Most of these provinces are located in the Mantaro river basin characterized by fertile lowlands and high population density (especially in the surrounding areas of the two major cities, Huancayo and Ayacucho). On the contrary, the South sector represented by larger desolate highland extents showed a prevalent very low proportion of area change (Fig 3). These results agree with similar findings in the Andes that remarked the driven role of high population density predicting agricultural expansion (Caycho-Ronco et al., 2009; Haller, 2012), while isolated rural communities have little motivation to advance in their land beyond subsistence farming (Swinton & Quiroz, 2003).

The second important pattern assessed in central high-Andean moist Puna was described by two trajectories concerning cropland extent. The first trend described a process of agricultural expansion predicted by population growth during 2000-2009 (Figures 3a and 4). This period was characterized by an internal high migration within the Mantaro Valley's that promoted the rapid growth of commercial farming in the lowlands (Haller & Borsdorf, 2013; Stepputat & Nyberg Sørensen, 2001). Whereas, the second trend showed farming land decrease during 2009-2013 linked to high population density and low schooling percentage (Fig. 5B). Fonte *et al.* (2012) and Skarbø and VanderMolen (2016) confirmed that population increase result in soil degradation pushing farmers to crop higher elevations with more favorable conditions. In the same way, Agudelo-Patiño

and Miralles i Garcia (2015) reported that the city growth reduced agricultural peri-urban systems in an Andean metropolitan area.

The third spatial pattern showed a trajectory of forestland extent decrease over the two-time steps and across half of provinces in the central moist Puna primarily defined by high population density, low family income and education (Fig 4). Forest area degraded (replaced by shrublands) more intensely during 2000-2009 (Fig 3f), mainly caused by overgrazing and controlled burning, which are principal drivers assessed in previous work (Fjeldså, 2002; Hosonuma et al., 2012; Josse, Cuesta, Navarro, Barrena, Cabrera, Chacón-Moreno, et al., 2009). Although deforestation provinces were correlated to agricultural expansion, it can be said that it did not represent an important process (24 km^2 of forest was reduced). On the other hand, during 2009-2013, few provinces had a forest decline not well explained by low population density and middle percentage of adults with complete secondary school.

In that sense, although our research focused on causal factors of the land-use change, there is a lack for explaining the observed spatial patterns that suggest further assessment.

4.2. Associations between land-change dynamics and ecosystem services

4.2.1. Capacity matrix

The involvement of 63 national and international experts with recognized experience developing ecological studies in the research field and being free to fulfil only the well-known LULC/regulating ES connections increased the confidence of the capacity matrix. The starting list of experts was short and grew by their suggestions as a "snow ball" sampling technique (Patton, 2002), taking the example by Scolozzi, Morri and Santolini (2012). Nevertheless, the final respondent pool was carefully selected from the larger number of qualified references following the indications by Jacobs *et al.* (2015). This strategy assured a high rate of participation (68%, 43 experts were interviewed) in a low period (07 weeks). Finally, after removing outliers, an average of 39 interventions was computed getting low variability in the final scores and reaching a stable mean, in concordance with Campagne *et al.*(2017), and validated by the results of the sensitivity analysis.

Experts favorably scored low forest and peatbogs and high-Andean wetlands, in a certain way expressing comparable opinions with specialists from around the world (Burkhard

et al., 2014; Depellegrin et al., 2016; Montoya-Tangarife et al., 2017). On the contrary, urban zones were scored as low as possible for many of the experts, coinciding with results from matrix model international studies (Bhandari et al., 2016; Burkhard et al., 2012, 2014; Sohel et al., 2015). Agricultural areas got medium-low potential supply showing similar analyses pointed, in other studies (Affek & Kowalska, 2017; Koschke et al., 2012). Glaciers and water bodies were highlighted as water flow controllers matching scores from Burkhard *et al.* (2014). Forest plantations had medium-high attention from experts, these scores were slightly higher from the ones expressed by Montoya-Tangarife *et al.* (2017) with identical species. Natural grasslands and shrublands develop important functions in the study area by their nature and spatial magnitude, as concerned by the practiced.

At the regional scale, the ES matrix showed that the territory provides a richness of regulating ecosystem services. Whereas, the same landscape presented a medium-low potential for crops and livestock.

4.2.2. Cluster analysis

Cluster analysis for LULC changes confirmed that most of the provinces were mainly described by a small set of dynamics, but with one dominant force. Only one bundle that included the largest LULC changes (DB4) was rather specialized in two dynamics. Three clusters were characterized by human actions and one by natural processes, just the bundle with the lowest ratio of change (DB3) had a quite diverse combination of forces. Urbanization and afforestation affected the lowest number of zones. Land-change dynamics described in the clusters are consistent with the land-changes stated in other studies in the Andean region (Aide & Grau, 2004; Brandt & Townsend, 2006; Pestalozzi, 2000; Tovar et al., 2013; K. R. Young, 2009).

Change over time analysis in pairwise interactions among ES described a strong significant correlation, revealing trade-offs among provisioning and regulating services; and synergies concerning the same ES sector. At similar landscapes, livestock trade-off global climate regulation, water flow regulation (Pan et al., 2014) and regulation of soil erosion (Petz et al., 2014). Turner *et al.* (2014) assessed a strong relationship between provisioning services (crops and livestock) and negative interaction with water purification. In an agricultural landscape, a pattern of trade-offs was found between provisioning and regulating ecosystem services (Crouzat et al., 2015). Agudelo-Patiño

and Miralles i Garcia (2015) indicated that provision of crops compromised water flow regulation in an Andean urban mountain system.

4.2.3. Associations between clusters of land-change dynamics and ecosystem service trends

ES bundles showed four different trends that linked the five land-change clusters establishing four types of associations. Provinces DSE1 were found in both time periods covering 72% and 69% percent of the territory, respectively. Although this landscape was the less undisturbed (ΔCH=7%), accumulated the 38% of deforestation (during first-time period), 35% of agricultural expansion (in both time periods) and 85% of urbanization (during T2). Urbanization has negative effects on water infiltration (Agudelo-Patiño & Miralles i Garcia, 2015) initiating surface run-off (Nakayama et al., 2007) and losses of carbon stocks and crops (Eigenbrod et al., 2011).

Link DES2 displayed eleven provinces that increased regulating ES potential due to an important process of agricultural de-intensification in T2 (79% of the total change caused by this dynamic in the study area over 13 years). Farming reduction co-occurred with a very low intensity of deforestation and a small increase of farming land (10% and 12% of the total change caused by each dynamic in the study area, respectively). The abandonment of marginal agricultural lands facilitates ecosystem recovery (Aide & Grau, 2004). Loss of soil fertility indicates shrublands regeneration (Rubiano et al., 2017). Evergreen vegetation regrows in natural fallow lands controlling soil erosion (Aguilera et al., 2013). Abandoned pastures contribute to C-sequestration (Knoke et al., 2014).

The expansion of agriculture was the dominant dynamic in association DES3 and occurred in the first-time step. Eight provinces had an enlargement of provisioning services and a high reduction of regulating ES (accumulated the 49%, 38% and 64% of the total change caused by agricultural expansion, deforestation and afforestation over the study period, respectively). It is proved that appropriate climatic and soil conditions support crop development in higher elevation areas (Postigo, 2014; Tito et al., 2018) which leads to the reduction of natural grasslands and therefore a potential reduction in water flow regulation and livestock services (Rolando, Turin, et al., 2017).

Association DES4 (accumulated 20% of the total change caused by natural processes in the study area) included two provinces in the initial time period with high loss of water flow regulation primarily due to glaciers retreat. In Peru, loss in surface area of glaciers

is manifested in the last two decades (Rabatel et al., 2013) that may have an impact on water resources (López-Moreno et al., 2014) and arise land for grazing and farming (K. R. Young, 2014).

4.2.4. Determinants for land-change dynamics and ecosystem services

Local social-ecological determinants explained where changes in associations of land-change dynamics and ES trends occurred across the moist Puna. Provinces (DES1) characterised by low human-altered landscapes were quite inaccessible from Lima (the capital city of Peru) and with a very low population density, whereas landscapes dominated by agricultural expansion were associated with a growing population density and developed road network. Areas (DES2) distinguished by a rise of regulating services were associated with a reduction of fuel wood consumption, whereas provinces with high deforestation were related to an increase in firewood use. Provinces defined by a growth of ES provision (DES4) were correlated to a high promotion of alpaca breeding.
Our study focuses on cluster analysis over time on a provincial scale, since in Peru land planning at local level is regulated by provincial municipalities (Organic Law of Municipalities No. 27972, 27 of May of 2003). The integration of ES in planning depends on the governmental planning instruments (Albert et al., 2014), therefore our study might promote and facilitate the incorporation of ES at multiple scales. Furthermore, in relation to the temporal scale of 13 years, the tendency of changes occurred as consequences of land management activities were observable in the territory. However, long historical data can improve the understanding of ES dynamics (Egarter Vigl et al., 2017; Lautenbach et al., 2011; Renard et al., 2015), but in the study area, availability and quality of past LULC models are absent.

4.3. Implications of choosing different assessment method and scale of observation for the management of ecosystem services

In our study, the ES matrix contributes to the assessment of relationships between ES, applying two different methods (static and dynamic) across four scales of observation over time. At the spatial scale level, it revealed several findings consistent with those found by comparable biophysical assessment (Ciara Raudsepp-Hearne & Peterson, 2016). We analyzed the differences between each assessment method by comparing the

results of standard metrics at each spatial scale over time. Subsequently, we discuss the main findings of the study validated by the sensitivity analysis (Table 9) and organized as scale and assessment method effects that might have implications on ES management.

Assessment Method Effect	Spatial Scale Effect
• Configuration: disagreement in the direction of the relationships between multiple ES. • Spatial patterns: static cluster analysis captured only a snapshot of ES bundles at different years, whereas cluster analysis with ΔES values displayed dynamics of ES bundles.	• Configuration: static cluster analysis displayed a trend towards more similarities among bundle types for large spatial scales, whereas dynamic cluster analysis showed a similar trend of positive and negative change in the ES supply at the three smaller spatial scales. • Spatial patterns: static cluster analysis suggested higher similarities between bundles at the municipal level and the two grid-scales, whereas dynamic cluster analysis showed some consistency across spatial scales. • Historical trajectories: both cluster analyses detected: (1) a trend towards a high percentage of land change for large spatial scales, and (2) a trend towards a high number of trajectories for fine spatial scales.

Table 9: Scale and assessment method effects on bundles of ecosystem services

4.3.1. Effects of different cluster assessments on bundles of ecosystem services

Depending on the cluster assessment, we found relationships between multiple ES that shifted in different ways. This finding agrees with previous work that also confirmed that the chosen method influences the result (H. Lee & Lautenbach, 2016; Tomscha & Gergel, 2016; Vallet et al., 2018). In that sense, in our study, "static bundles" suggested a positive spatial co-occurrence among the seven ES. On the contrary, "dynamic bundles" proposed a negative relationship between provisioning and regulating services. The synergy detected with the static assessment shows an opportunity to enhance multiple ES simultaneously. However, it missed the trade-off between regulating and provisioning services, and it could represent an unexpected loss of success for ES management. In fact, it implicates missing opportunities for win–win solutions that involve investments in conservation, restoration, and sustainable ecosystem use (de Groot et al., 2010).

The spatial distribution of bundles captured by each cluster assessment showed differences. Thus, ES values displayed a landscape characterized by bundles with a specific diversity and abundance of ecosystem services supply at each time-step. On the other hand, ΔES values addressed the dynamics of ES bundles over the two time-periods.

This last interpretation may facilitate the understanding of the instabilities that produce the temporal dynamics on ecosystems since trends expose whether there has been a change and the specified event that caused it (de Gruijter et al., 2006). This finding concerning "dynamic bundles" is consistent with previous research for the knowledge of land-changes dynamics (Madrigal-Martínez & Miralles i García, 2019b).

4.3.2. Effects of different scales of observation on bundles of ecosystem services

The static assessment of bundles suggested that the configuration followed a trend towards more similarities at large spatial scales (Fig 11). This effect may explain that large spatial units follow a multifunctional landscape allowing relationships between ES to concur in synergy. It is understandable because the impacts of management actions at a fine-scale may be insignificant at a larger spatial scale if the land-use type affected is scarce, which is related to the capacity to capture local heterogeneity. Thus, the relationships between ES are conditioned by the geographical size of any single land-use change in the spatial unit. Consequently, at the grid scales, bundle types were more specialized according to one LULC unit (this was evident at the fine-grid scale). However, the provincial level provided a comparative abundance of ES because they were characterized by a similar combination of land-units. This similarity indicates comparable levels of land-use diversity that produces akin multifunctionality at large spatial units. Although multifunctionality is location related (Stürck & Verburg, 2017), this effect is observed in previous work of ES bundles across different administrative levels (Hamann et al., 2015; Ciara Raudsepp-Hearne & Peterson, 2016). For instance, this generalization of the configuration can be inconvenient when we need to identify areas of highest/lowest supply of ES (hotspots/coldspots) for spatial prioritization or designing green infrastructure. In that sense, the bundles of small size only persist across grid-scales. It implies a loss of bundle diversity when we upscale, which agrees with Zen *et al.* (2019). Then, large scales (dramatically at the provincial level) may fail to observe determinant factors and their influence on the sustainability of the ecosystems and their services. It reinforces the assumption that the increase in the spatial scale of observation brings a homogenization of the landscape (M. G. Turner et al., 1989), and only the main land-changes are significant (Madrigal-Martínez & Miralles i García, 2019b).

At the three smaller spatial scales, bundles showed a similar configuration of positive and negative change in ES supply (Fig 12B), reflecting higher accuracy with the rate of

change established by the different drivers (climate change, and technological improvement of agriculture and forestry). Needless to say, these bundles offer a basic view of the dynamic of ES that may help in planning win–win solutions. However, this basic picture depends on the size of the spatial unit, since it determines the intensity of drivers of change. In our study, as large as the spatial scale was, the land-use change impacts were more buffered. Although the provincial bundles detailed many similarities with the smaller scales of observation, the contrasts involve caution when using this spatial scale for the management of ecosystem services.

Static cluster analysis suggested high similarities between the spatial distribution of bundles at the municipal level and the two grid-scales. Consequently, it manifested fair robustness across the three smaller spatial scales, which differed with Raudsepp-Hearne and Peterson (2016). It may be related to the Andean study area, which is a landscape with ecosystem services more evenly distributed, and some amount of each ES facilitating multifunctionality can be found at the municipality level. Thus, the variation of bundling across a territory depends on the spatial heterogeneity of services since spatial homogeneity uncovers the same type of bundle across spatial scales. This diversity of findings recommends that researchers and decision-makers should be aware of the size and the heterogeneity of the spatial units to improve the aims of ES analyses (Verhagen et al., 2016). Even though many times, there are limitations related to data scarcity or availability, which impede the research from being conducted optimally. We agree with previous research that considering at least two spatial scales should assure robustness (Felipe-Lucia et al., 2014; Scholes et al., 2013), but we suggest a fine-grid scale and the municipality level. A fine-scale is important to show specific spots at local level that give a better panorama for well-informed planning decisions, whereas, at the municipality level is where political decisions are made and socioeconomic data are available. However, it is worth emphasizing that our study shows sufficient consistency between the municipal scale and the grid-scales.

The spatial distribution of bundles resulting from ΔES values revealed some consistency across spatial scales. However, bundling generalization was more evident as the scale of observation increased. This effect produces homogeneity at broad resolutions that can lead to shape a territory with similar land-use change intensity and overlooking fine-grained information needed for spatial conservation planning (Trabucchi et al., 2013). In our study site, at the provincial level, that generalization obscures changes in ecosystem services at lower levels that may be of importance for planning and management

solutions. However, Madrigal-Martínez and José Luis Miralles i García (2019) showed that, in research conditions of data scarcity, it is possible to address knowledge about land-change dynamics affecting ES that may help for policy and planning purposes at the provincial level.

For historical trajectories of bundles, both cluster analyses indicated that the area providing any given bundle changes higher at broad spatial scales over time. It implies that objects (land-units) within a large spatial unit are strongly associated, and a substantial change in one of them affects the total, whereas minor and static zones are overlooked. In our study area, this was more evident at the provincial level, in which the variation in ES supply of a given province was due to changes only in a few land-units. It is a consequence of upscaling that has direct impacts on the intensity of land-use change affecting ES. Low intense land-use change is not significant at broad scales (Madrigal-Martínez & Miralles i García, 2019b). In that sense, only at the grid-scales minor land-use changes that configured small size bundles were detected. This effect was detected in both cluster analyses and showed a trend towards a high number of trajectories for fine spatial scales. For example, we observe that bundles characterized by an increase in regulating services at grid-scales disappear at large (municipal and provincial). It reveals that changes at larger spatial scales have a buffer effect, whereas, at the fine-scales, bundles are more sensitive to temporal changes shaped by the direct local-scale drivers. This finding supports the assumption that knowledge of local contexts of ES is policy-relevant since their changes in values and demand are finer observable over time (Hein et al., 2016; Hou et al., 2013). Therefore, the assessment of the spatial extension under the influence of drivers could help with the understanding of the stability of ES provision, endorsing robustness for the development of sustainable management and conservation strategies.

4.4. Methodological Limitations

In this study, the analyses presented should be understood as using the best existing data of an acceptable quality to admit a robust demonstration. Even so, the method (ES matrix) brings potential limitations to the study, and technical and thematic uncertainties (Hou et al., 2013). In that sense, we list the more relevant:

- The capacity matrix simplifies landscape functionality producing uncertainties in the quantification of ES (e.g., regulating services). It is due to this that some ES

are not only dependent on the presence of certain land use/land cover types but also their spatial configuration.

- Moreover, management actions on each land-use may affect ES flow differently (specially in provisioning services), and this effect could be measured vaguely for the matrix.
- Another limitation lies in that the reduced and diverse data sources of land use/land cover classes made a generalization of the landscape necessary, which could influence the bundles that emerge at larger spatial scales. In fact, a more precise number of land use/land cover classes could result in the reconfiguration of bundles (Verhagen et al., 2016).
- Additionally, in ES matrix models, the multifunctionality is strongly dependent on the number of services provided by the different land use/land cover types (Burkhard et al., 2009).
- On the other hand, when data at a fine-scale were summarized at the administrative levels (aggregation effect), they could cause a loss of information (Bolliger & Mladenoff, 2005).
- Finally, the data source (the map of high-Andean ecosystems) has a vague delimitation for two land units (agricultural areas and forest plantation), comprehending them in only one land-use category (Areas modified by human action). However, we considered this limitation of minor importance because this aspect was clarified using the land-use types from the two official flora cover maps.

CHAPTER 5. CONCLUSION

5.1. Conclusions

The ecosystems identified in the moist Puna have an important role in providing regulating services. Among them, low forests, shrublands, natural grasslands, and peatbogs and high-Andean wetlands are the ecosystems that dominate the landscape. Furthermore, glaciers denoted a high potential supply of regulating water flow, whereas water bodies stood out for their capacity to purify water. These semi-natural areas have the capacity to supply all the services studied when they are in optimal conditions. However, these ecological functions are continuously threatened by human interventions. We presented a transparent approach about spatial patterns of land-use changes in in the moist Puna that can contribute to a better understanding of complex social-ecological mountain landscapes. Understanding the spatial patterns of land-changes in the extent and their explanatory variables, is important for clarifying their trajectories. Therefore, typifying land-use change dynamics of the moist Puna would be a beneficial and interesting field for future research. Moreover, our study could be used as starting point for the development of research focusing on the impact of the land-use change patterns on biodiversity and ecosystem services.

Overall, our analysis addressed agricultural expansion, agricultural de-intensification, natural processes and deforestation as the most critical land-change dynamics and their grouping across the high-Andean region through the 13 years. These clusters configured four types of ES bundles that might clarify ES complexity and help management purposes and decision-making. The results of the study have demonstrated that different patterns of land-change dynamics can have similar influence on the ES bundle development. The transformation of large areas is not necessarily equivalent to high variations in ES supply, whereas small land alterations are corresponding to slight impacts in ES provision.

Despite all these threats to ecosystems, we find strengths based on the spatial planning initiatives that promote the provision of ES in the moist Puna. To the best of our knowledge, the Peruvian government is the first state in South America that regulated the "Pay for Ecosystem Services" mechanism by Law. This legal support offers to providers of ES a security related to the financial incentive that, through an agreement, could enlarge the extents of ecosystems under sustainable use. Added to this, there is the institutional strength offered by the Ministry of the Environment and the National

Superintendence of Sanitation Services, that give stable conjuncture and promote the "Pay for Ecosystem Services" mechanism.

Moreover, we developed a study that addressed the effects of different cluster methods for assessing bundles of ES across different scales of observation over time, using an example in the high-Andean moist Puna. We aimed to detect the differences in applying two cluster analyses—for ES values and ΔES values—and the effects of different scales of observation—two administrative levels and two grid resolutions—on ES bundles over time. To address these objectives, we investigated two hypotheses: (1) bundles of ES differ in composition due to the method applied for assessing them; (2) the configuration of the bundles is affected by the scale of observation. Our analysis uncovered consistent differences suggesting that the selection of a method for assessing bundles of ES might define the results, and the scale of observation influenced them.

"Static" bundles suggested synergies between provisioning and regulating services, whereas "dynamic" indicated negative relationships. Then, the assumption of a general pattern of trade-offs between these groups of services needs to be analyzed in detail (Qiao et al., 2019; Vallet et al., 2018). The diverse interpretations found in our study suggest that both assessment methods have implications for management of ES, and both can be complementary to obtain better contributions for decision-making. However, if research objectives are focused on the understanding of the instabilities that produce the temporal dynamics on ecosystems, we recommend the assessment of "dynamic" bundles since these are more sensitive to changes of the different drivers across spatial scales. Moreover, between 0.25 or 10^2 km^2 there is no much difference, but large administrative levels (e.g. 10^3 km^2) need caution.

The differences addressed over time showed confident generalization to advise the pros and cons of which spatial scale to use. The municipality level (10^2 km^2) showed sufficient consistency with grid-scales, which may be enough to guide policy, as other studies highlighted (Ciara Raudsepp-Hearne & Peterson, 2016; Roces-Díaz et al., 2018). However, for spatial conservation, the fine-grid scale could be needed to visualize small patch sizes. Then, as a rule, resulting from the study, ES bundles at grid scales are characterized by a high level of dispersion and small patch size disappear or are imperceptible at administrative levels. In that sense, bundles at administrative levels tend to describe landscape multifunctionality, whereas fine-grained resolutions define more specialized bundles. Indeed, at heterogeneous landscapes, bundling becomes complex, whereas bundles are very similar across different spatial scales on homogeneous

landscapes. In that way, we achieve that the central moist Puna is composed of homogeneous landscapes, characterize by natural grasslands, that provide similar bundles of ecosystem services across space.

Finally, we have shown that the ES matrix and standard metrics display the implications of choosing a method and a scale of observation in bundle assessment. To the best of our knowledge, this is the first study in which such a comprehensive step by step framework comparing "dynamic" and "static" bundles of ES has been developed. Bearing in mind the potential of bundles to support decision-making, the results might help the choice of bundling methods during the design of research projects. Our findings fill the knowledge gap on relationships between multiple ES utilizing cluster techniques robustly.

5.2. Further research

The measuring of ecosystem services is a global task. It is necessary to have detailed and quality cartographic data of different variables. But, in landscapes with data scarcity (insufficient variables), the ES matrix model solves this handicap. It is needed to mention that the ES matrix model method facilitates an approach to reality without replacing it. Also, it should be noted that this research covers an area of 64,025 km^2, and this is a first appraisal completed with limited time and no funding resources. However, the study identifies information gaps and future research areas:

- This research primarily focuses on regulating and provisioning ES. A more exhaustive list of this type of ES could be of interest. Ecosystem services related to lifecycle maintenance, habitat, and gene pool protection are needed to improve the land management of the high-Andean territory. Also, cultural ES related to the physical, intellectual, and experiential interactions with the natural environment may be measured to prevent disturbances.
- More research is required to assess ES bundles at different spatial extensions. The ES matrix developed could be used to map ES at the whole moist Puna ecosystem.
- It is needed to give attention to landscapes with diverse levels of spatial heterogeneity. Comparing ES bundles at different levels of heterogeneity could improve the land management actions.
- To elaborate a detailed ES matrix that could incorporate a higher number of LULC units. To do this task is needed satellite images with advanced resolution. In that way, it is also required an update of the cartographical data.

REFERENCES

Abson, D. J., von Wehrden, H., Baumgärtner, S., Fischer, J., Hanspach, J., Härdtle, W., Heinrichs, H., Klein, A. M., Lang, D. J., Martens, P., & Walmsley, D. (2014). Ecosystem services as a boundary object for sustainability. *Ecological Economics*, *103*, 29–37. https://doi.org/10.1016/j.ecolecon.2014.04.012

Affek, A. N., & Kowalska, A. (2017). Ecosystem potentials to provide services in the view of direct users. *Ecosystem Services*, *26*, 183–196. https://doi.org/10.1016/j.ecoser.2017.06.017

Agudelo-Patiño, L. C., & Miralles i Garcia, J. L. (2015). Design and management of the metropolitan green belt of Aburrá Valley, Colombia. *The Sustainable City X*, *1*, 193–203. https://doi.org/10.2495/sc150181

Aguilera, J., Motavalli, P., Valdivia, C., & Gonzales, M. A. (2013). Impacts of Cultivation and Fallow Length on Soil Carbon and Nitrogen Availability in the Bolivian Andean Highland Region. *Mountain Research and Development*, *33*(4), 391–403. https://doi.org/10.1659/MRD-JOURNAL-D-12-00077.1

Aide, T. M., Clark, M. L., Grau, H. R., López-Carr, D., Levy, M. A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M. J., & Muñiz, M. (2013). Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). *Biotropica*, *45*(2), 262–271. https://doi.org/10.1111/j.1744-7429.2012.00908.x

Aide, T. M., & Grau, H. R. (2004). Globalization, migration, and latin american ecosystems. In *Science* (Vol. 305, Issue 5692, pp. 1915–1916). https://doi.org/10.1126/science.1103179

Albert, C., Aronson, J., Fürst, C., & Opdam, P. (2014, October 10). Integrating ecosystem services in landscape planning: requirements, approaches, and impacts. *Landscape Ecology*, *29*(8), 1277–1285. https://doi.org/10.1007/s10980-014-0085-0

Anselm, N., Brokamp, G., & Schütt, B. (2018). Assessment of Land Cover Change in Peri-Urban High Andean Environments South of Bogotá, Colombia. *Land*, *7*(2), 75. https://doi.org/10.3390/land7020075

Balthazar, V., Vanacker, V., Molina, A., & Lambin, E. F. (2015). Impacts of forest cover change on ecosystem services in high Andean mountains. *Ecological Indicators*, *48*, 63–75. https://doi.org/10.1016/j.ecolind.2014.07.043

Baraer, M., Mckenzie, J. M., Mark, B. G., Bury, J., & Knox, S. (2009). Characterizing contributions of glacier melt and groundwater during the dry season in a poorly

gauged catchment of the Cordillera Blanca (Peru). In *Adv. Geosci* (Vol. 22). www.adv-geosci.net/22/41/2009/

Bhandari, P., KC, M., Shrestha, S., Aryal, A., & Shrestha, U. B. (2016). Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal. *Applied Geography*, *69*, 25–34. https://doi.org/10.1016/j.apgeog.2016.02.003

Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Früh-Müller, A., Machnikowski, F., Mader, V. L., Nilsson, L., Sasaki, K., Rundlöf, M., Wolters, V., & Smith, H. G. (2015). Ecosystem services-current challenges and opportunities for ecological research. *Frontiers in Ecology and Evolution*, *2*(JAN). https://doi.org/10.3389/fevo.2014.00087

Blancas, A. N. I., Torre-Cuadros, M. de los Á. La, & Carrera, G. A. M. (2018). Using Foresight to Gain a Local Perspective on the Future of Ecosystem Services in a Mountain Protected Area in Peru. *Mountain Research and Development*, *38*(3), 192–202. https://doi.org/10.1659/mrd-journal-d-17-00090.1

Boillat, S., Scarpa, F. M., Robson, J. P., Gasparri, I., Aide, T. M., Aguiar, A. P. D., Anderson, L. O., Batistella, M., Fonseca, M. G., Futemma, C., Grau, H. R., Mathez-Stiefel, S. L., Metzger, J. P., Ometto, J. P. H. B., Pedlowski, M. A., Perz, S. G., Robiglio, V., Soler, L., Vieira, I., & Brondizio, E. S. (2017). Land system science in Latin America: challenges and perspectives. In *Current Opinion in Environmental Sustainability* (Vols. 26–27, pp. 37–46). Elsevier. https://doi.org/10.1016/j.cosust.2017.01.015

Bolliger, J., & Mladenoff, D. J. (2005). Quantifying spatial classification uncertainties of the historical Wisconsin landscape (USA). *Ecography*, *28*(2), 141–156. https://doi.org/10.1111/j.0906-7590.2005.03955.x

Brandt, J. S., & Townsend, P. A. (2006). Land use - Land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. *Landscape Ecology*, *21*(4), 607–623. https://doi.org/10.1007/s10980-005-4120-z

Burkhard, B., Kandziora, M., Hou, Y., & Müller, F. (2014). Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landscape Online*, *34*(1), 1–32. https://doi.org/10.3097/LO.201434

Burkhard, B., Kroll, F., Müller, F., & Windhorst, W. (2009). Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments. *Landscape Online*, *15*(1), 1–22. https://doi.org/10.3097/LO.200915

Burkhard, B., Kroll, F., Nedkov, S., & Müller, F. (2012). Mapping ecosystem service supply, demand and budgets. *Ecological Indicators*, *21*, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019

Campagne, C. S., Roche, P., Gosselin, F., Tschanz, L., & Tatoni, T. (2017). Expert-based ecosystem services capacity matrices: Dealing with scoring variability. *Ecological Indicators*, *79*, 63–72. https://doi.org/10.1016/j.ecolind.2017.03.043

Caycho-Ronco, J., Arias-Mesia, A., Oswald, A., Esprella-Elias, R., Rivera, A., F. Yumisaca, J., & Andrade-Piedra. (2009). Tecnologías sostenibles y su uso en la producción de papa en la región altoandina. *Revista Latinoamericana de La Papa*, *15*(1), 20–37.

Charrad, M., Ghazzali, N., Boiteau, V., & Maintainer, A. N. (2015). *NbClust Package for determining the best number of clusters*. https://cran.r-project.org/web/packages/NbClust/NbClust.pdf

Cochi Machaca, N., Condori, B., Pardo, A. R., Anthelme, F., Meneses, R. I., Weeda, C. E., & Perotto-Baldivieso, H. L. (2018). Effects of grazing pressure on plant species composition and water presence on bofedales in the Andes mountain range of Bolivia. *Mires and Peat*, *21*(15), 1–15. https://doi.org/10.19189/MaP.2017.OMB.303

Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10.1177/001316446002000104

Cord, A. F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., & Volk, M. (2017). Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. In *Ecosystem Services* (Vol. 28, pp. 264–272). Elsevier. https://doi.org/10.1016/j.ecoser.2017.07.012

Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F., Verkerk, P. J., & Lavorel, S. (2015). Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. *Journal of Applied Ecology*, *52*(5), 1145–1155. https://doi.org/10.1111/1365-2664.12502

Cui, F., Tang, H., Zhang, Q., Wang, B., & Dai, L. (2019). Integrating ecosystem services supply and demand into optimized management at different scales: A case study in Hulunbuir, China. *Ecosystem Services*, *39*.

https://doi.org/10.1016/j.ecoser.2019.100984

Custodio, M., Chanamé, F., Pizarro, S., & Cruz, D. (2018). Quality of the aquatic environment and diversity of benthic macroinvertebrates of high Andean wetlands of the Junín region, Peru. *The Egyptian Journal of Aquatic Research*, *44*(3), 195–202. https://doi.org/10.1016/J.EJAR.2018.08.004

Dade, M. C., Mitchell, M. G. E., McAlpine, C. A., & Rhodes, J. R. (2019). Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. In *Ambio* (Vol. 48, Issue 10, pp. 1116–1128). Springer Netherlands. https://doi.org/10.1007/s13280-018-1127-7

de Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*(3), 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

de Gruijter, J. J., Bierkens, M. F. P., Brus, D. J., & Knotters, M. (2006). Sampling for Natural Resource Monitoring. In *Sampling for Natural Resource Monitoring*. Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-33161-1

de Valença, A. W., Vanek, S. J., Meza, K., Ccanto, R., Olivera, E., Scurrah, M., Lantinga, E. A., & Fonte, S. J. (2017). Land use as a driver of soil fertility and biodiversity across an agricultural landscape in the Central Peruvian Andes. *Ecological Applications*, *27*(4), 1138–1154. https://doi.org/10.1002/eap.1508

Deng, X., Li, Z., & Gibson, J. (2016). A review on trade-off analysis of ecosystem services for sustainable land-use management. In *Journal of Geographical Sciences* (Vol. 26, Issue 7, pp. 953–968). Science in China Press. https://doi.org/10.1007/s11442-016-1309-9

Depellegrin, D., Pereira, P., Misiunė, I., & Egarter-Vigl, L. (2016). Mapping ecosystem services potential in Lithuania. *International Journal of Sustainable Development and World Ecology*, *23*(5), 441–455. https://doi.org/10.1080/13504509.2016.1146176

der Biest Van, D'Hondt, R., Jacobs, S., Landuyt, D., Staes, J., Goethals, P., & Meire, P. (2014). EBI: An index for delivery of ecosystem service bundles. *Ecological Indicators*, *37*, *Part A*, 252–265. https://doi.org/10.1016/j.ecolind.2013.04.006

Dixon, John; Gulliver, Aidan; Gibbon, David; Hall, M. (2001). Farming Systems and Poverty Farming Systems and Poverty:Improving Farmers' Livelihoods in a Changing World. *FAO and World Bank, Rome and Washington DC*, 412.

https://doi.org/10.1017/S0014479702211059

Dou, H., Li, X., Li, S., & Dang, D. (2018). How to Detect Scale Effect of Ecosystem Services Supply? A Comprehensive Insight from Xilinhot in Inner Mongolia, China. *Sustainability*, *10*(10), 3654. https://doi.org/10.3390/su10103654

Du, X., Jin, X., Yang, X., Yang, X., & Zhou, Y. (2014). Spatial pattern of land use change and its driving force in Jiangsu province. *International Journal of Environmental Research and Public Health*, *11*(3), 3215–3232. https://doi.org/10.3390/ijerph110303215

Duchicela, S. A., Cuesta, F., Pinto, E., Gosling, W. D., & Young, K. R. (2019). Indicators for assessing tropical alpine rehabilitation practices. *Ecosphere*, *10*(2), e02595. https://doi.org/10.1002/ecs2.2595

Egarter Vigl, L., Tasser, E., Schirpke, U., & Tappeiner, U. (2017). Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. *Regional Environmental Change*, *17*(8), 2237–2250. https://doi.org/10.1007/s10113-017-1132-6

Egoh, B. N., Reyers, B., Rouget, M., & Richardson, D. M. (2011). Identifying priority areas for ecosystem service management in South African grasslands. *Journal of Environmental Management*, *92*(6), 1642–1650. https://doi.org/10.1016/j.jenvman.2011.01.019

Eigenbrod, F., Bell, V. A., Davies, H. N., Heinemeyer, A., Armsworth, P. R., & Gaston, K. J. (2011). The impact of projected increases in urbanization on ecosystem services. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1722), 3201–3208. https://doi.org/10.1098/rspb.2010.2754

Ektvedt, T. M., Vetaas, O. R., & Lundberg, A. (2012). Land-cover changes during the past 50 years in the semi-arid tropical forest region of northern peru. *Erdkunde*, *66*(1), 57–75. https://doi.org/10.3112/erdkunde.2012.01.05

ESRI. (2014). ArcGIS Desktop: Release 10.3. In *Redlands CA* (p. Environmental Systems Research Institute.). https://doi.org/10.1209/epl/i2001-00551-4

European Environment Agency. (2013). *Common International Classification of Ecosystem Services (CICES)*. Cices. http://cices.eu/

Feixiang, S. U. N., Yihe, L. Y. U., Bojie, F. U., & Jian, H. U. (2016). Hydrological Services by Mountain Ecosystems in Qilian Mountain of China : A Review. *Chinese Geographical Science*, *26*(2), 174–187. https://doi.org/10.1007/s11769-015-0791-9

Felipe-Lucia, M. R., Comín, F. A., & Bennett, E. M. (2014). Interactions Among Ecosystem Services Across Land Uses in a Floodplain Agroecosystem. *Ecology and Society*, *19*(1), art20. https://doi.org/10.5751/ES-06249-190120

Fjeldså, J. (2002). Polylepis forests – vestiges of a vanishing ecosystem in the Andes. *Ecotropica*, *8*, 111–123.

Fonte, S. J., Vanek, S. J., Oyarzun, P., Parsa, S., Quintero, D. C., Rao, I. M., & Lavelle, P. (2012). Pathways to Agroecological Intensification of Soil Fertility Management by Smallholder Farmers in the Andean Highlands. In *Advances in Agronomy* (Vol. 116, pp. 125–184). https://doi.org/10.1016/B978-0-12-394277-7.00004-X

Frey, B. J., & Dueck, D. (2007). Clustering by passing messages between data points. *Science*, *315*(5814), 972–976. https://doi.org/10.1126/science.1136800

Geist, H. J., & Lambin, E. F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience*, *52*(2), 143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:pcaudf]2.0.co;2

Geological Mining and Metallurgical Institute. (2018). *Mapa catastro minero del Perú* (p. 1).

Gibbon, A., Silman, M. R., Malhi, Y., Fisher, J. B., Meir, P., Zimmermann, M., Dargie, G. C., Farfan, W. R., & Garcia, K. C. (2010). Ecosystem Carbon Storage Across the Grassland–Forest Transition in the High Andes of Manu National Park, Peru. *Ecosystems*, *13*(7), 1097–1111. https://doi.org/10.1007/s10021-010-9376-8

Gobierno Regional de Ayacucho. (2013). *Zonificación Ecológica Económica - Ayacucho*.

Gobierno Regional de Huancavelica. (2013). *MESO ZONIFICACION ECOLOGICA y ECONOMICA DEL DEPARTAMENTO DE HUANCAVELICA.*

Grêt-Regamey, A., Brunner, S. H., & Kienast, F. (2012). Mountain Ecosystem Services: Who Cares? *Mountain Research and Development*, *32*(S1), S23–S34. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1

Gutiérrez B., N., Gärtner, S., López H., J. Y., Pacheco, C. E., & Reif, A. (2013). The recovery of the lower montane cloud forest in the Mucujún watershed, Mérida, Venezuela. *Regional Environmental Change*, *13*(5), 1069–1085. https://doi.org/10.1007/s10113-013-0413-y

Haines-Young, R., & Potschin, M. (2018). CICES V5. 1. Guidance on the Application of the Revised Structure. *Fabis Consulting*, *January*, 53. www.cices.eu

Haller, A. (2012). Vivid valleys, pallid peaks? Hypsometric variations and rural-urban land change in the Central Peruvian Andes. *Applied Geography*, *35*(1–2), 439–447. https://doi.org/10.1016/j.apgeog.2012.09.009

Haller, A., & Borsdorf, A. (2013). Huancayo Metropolitano. *Cities*, *31*, 553–562. https://doi.org/10.1016/J.CITIES.2012.04.004

Hamann, M., Biggs, R., & Reyers, B. (2015). Mapping social-ecological systems: Identifying "green-loop" and "red-loop" dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change*, *34*, 218–226. https://doi.org/10.1016/j.gloenvcha.2015.07.008

Hartman, B. D., Bookhagen, B., & Chadwick, O. A. (2016). The effects of check dams and other erosion control structures on the restoration of Andean bofedal ecosystems. *Restoration Ecology*, *24*(6), 761–772. https://doi.org/10.1111/rec.12402

Hein, L., van Koppen, C. S. A. K., van Ierland, E. C., & Leidekker, J. (2016). Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. *Ecosystem Services*, *21*, 109–119. https://doi.org/10.1016/j.ecoser.2016.07.008

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. In *Environmental Research Letters* (Vol. 7, Issue 4, p. 044009). IOP Publishing. https://doi.org/10.1088/1748-9326/7/4/044009

Hou, Y., Burkhard, B., & Müller, F. (2013). Uncertainties in landscape analysis and ecosystem service assessment. *Journal of Environmental Management*, *127*, S117–S131. https://doi.org/10.1016/j.jenvman.2012.12.002

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*(1), 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

INEI - National Institute of Statistics and Informatics. (n.d.-a). *III Censo Nacional Agropecuario 1994 (III CENAGRO)*. http://censos.inei.gob.pe/bcoCuadros/IIIcenagro.htm

INEI - National Institute of Statistics and Informatics. (n.d.-b). *National census*.

https://www.inei.gob.pe/estadisticas/censos/

INEI - National Institute of Statistics and Informatics. (2014). *Encuesta Nacional de Hogares*. https://webinei.inei.gob.pe/anda_inei/index.php/catalog/ENC_HOGARES

Jacobs, S., Burkhard, B., Van Daele, T., Staes, J., & Schneiders, A. (2015). 'The Matrix Reloaded': A review of expert knowledge use for mapping ecosystem services. *Ecological Modelling*, *295*, 21–30. https://doi.org/10.1016/j.ecolmodel.2014.08.024

Jameson, J. S., & Ramsay, P. M. (2007). Changes in high-altitude Polylepis forest cover and quality in the Cordillera de Vilcanota, Perú, 1956–2005. *Biological Conservation*, *138*(1–2), 38–46. https://doi.org/10.1016/J.BIOCON.2007.04.008

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., Chacón-Moreno, E., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009). *Ecosistemas de los Andes del Norte y Centro*. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. http://www.saber.ula.ve/handle/123456789/39336

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009a). *Ecosistemas de los Andes del Norte y Centro*. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. https://doi.org/10.1164/rccm.200702-271OC

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009b). *Mapa de ecosistemas de los andes del norte y centro. Bolivia,Colombia, Ecuador, Perú y Venezuela*. www.infoandina.org/ecosistemasandinos

Knoke, T., Bendix, J., Pohle, P., Hamer, U., Hildebrandt, P., Roos, K., Gerique, A., Sandoval, M. L., Breuer, L., Tischer, A., Silva, B., Calvas, B., Aguirre, N., Castro, L. M., Windhorst, D., Weber, M., Stimm, B., Günter, S., Palomeque, X., … Beck, E. (2014). Afforestation or intense pasturing improve the ecological and economic value of abandoned tropical farmlands. *Nature Communications*, *5*.

https://doi.org/10.1038/ncomms6612

Koschke, L., Fürst, C., Frank, S., & Makeschin, F. (2012). A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecological Indicators*, *21*, 54–66. https://doi.org/10.1016/j.ecolind.2011.12.010

Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M. R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P. J., Verburg, P. H., & Reenberg, A. (2016). Hotspots of land use change in Europe. *Environmental Research Letters*, *11*(6), 064020. https://doi.org/10.1088/1748-9326/11/6/064020

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, *28*(1), 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. *Biometrics*, *33*(1), 159. https://doi.org/10.2307/2529310

Lautenbach, S., Kugel, C., Lausch, A., & Seppelt, R. (2011). Analysis of historic changes in regional ecosystem service provisioning using land use data. *Ecological Indicators*, *11*(2), 676–687. https://doi.org/10.1016/j.ecolind.2010.09.007

Lavorel, S., Bayer, A., Bondeau, A., Lautenbach, S., Ruiz-Frau, A., Schulp, N., Seppelt, R., Verburg, P., Teeffelen, A. van, Vannier, C., Arneth, A., Cramer, W., & Marba, N. (2017). Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. In *Ecological Indicators* (Vol. 74, pp. 241–260). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2016.11.015

Lee, E., Livino, A., Han, S. C., Zhang, K., Briscoe, J., Kelman, J., & Moorcroft, P. (2018). Land cover change explains the increasing discharge of the Paraná River. *Regional Environmental Change*, *18*(6), 1871–1881. https://doi.org/10.1007/s10113-018-1321-y

Lee, H., & Lautenbach, S. (2016). A quantitative review of relationships between ecosystem services. *Ecological Indicators*, *66*, 340–351. https://doi.org/10.1016/j.ecolind.2016.02.004

Legendre, P. (2018). Numerical ecology. In *Encyclopedia of Ecology* (pp. 487–493). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10595-0

Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M. R., Metzger, M. J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P. H., Verkerk, P. J., & Kuemmerle, T. (2018). Archetypical patterns and trajectories of land systems in Europe.

Regional Environmental Change, *18*(3), 715–732. https://doi.org/10.1007/s10113-015-0907-x

Li, T., Lü, Y., Fu, B., Hu, W., & Comber, A. J. (2019). Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: enhanced services while depressed synergies. *Ecological Indicators*, *99*, 332–342. https://doi.org/10.1016/j.ecolind.2018.12.041

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., & Li, S. (2015). Systems integration for global sustainability. In *Science* (Vol. 347, Issue 6225). https://doi.org/10.1126/science.1258832

Locatelli, B., Lavorel, S., Sloan, S., Tappeiner, U., & Geneletti, D. (2017). Characteristic trajectories of ecosystem services in mountains. In *Frontiers in Ecology and the Environment* (Vol. 15, Issue 3, pp. 150–159). Wiley-Blackwell. https://doi.org/10.1002/fee.1470

López-Moreno, J. I., Fontaneda, S., Bazo, J., Revuelto, J., Azorin-Molina, C., Valero-Garcés, B., Morán-Tejeda, E., Vicente-Serrano, S. M., Zubieta, R., & Alejo-Cochachín, J. (2014). Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. *Global and Planetary Change*, *112*, 1–11. https://doi.org/10.1016/j.gloplacha.2013.10.010

Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*(12), 2365–2407. https://doi.org/10.1080/0143116031000139863

MA. (2005). *Ecosystems and human well-being: synthesis report*. www.islandpress.org

Madrigal-Martínez, S., & Miralles i García, J. L. (2019a). Understanding land use changes in the central high-Andean moist Puna. *WIT Transactions on Ecology and the Environment*, *238*.

Madrigal-Martínez, S., & Miralles i García, J. L. (2019b). Land-change dynamics and ecosystem service trends across the central high-Andean Puna. *Scientific Reports*, *9*(1), 9688. https://doi.org/10.1038/s41598-019-46205-9

Maldonado Fonkén, M. S. (2014). An introduction to the bofedales of the Peruvian High Andes. *Mires and Peat*, *15*(15), 1–13. http://www.mires-and-peat.net/,ISSN1819-754X

Mark, B. G., & Seltzer, G. O. (2003). Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *Journal of Glaciology*,

49(165), 271–281. https://doi.org/10.3189/172756503781830746

Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Del Amo, D. G., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I., Willaarts, B., González, J. A., Santos-Martín, F., Onaindia, M., López-Santiago, C., & Montes, C. (2012). Uncovering ecosystem service bundles through social preferences. *PLoS ONE*, *7*(6), e38970. https://doi.org/10.1371/journal.pone.0038970

Meacham, M., Queiroz, C., Norström, A. V., & Peterson, G. D. (2016). Social-ecological drivers of multiple ecosystem services: What variables explain patterns of ecosystem services across the Norrström drainage basin? *Ecology and Society*, *21*(1). https://doi.org/10.5751/ES-08077-210114

Metzger, M. J., Rounsevell, M. D. A., van den Heiligenberg, H. A. R. M., Pérez-Soba, M., & Hardiman, P. S. (2010). How personal judgment influences scenario development: An example for future rural development in Europe. *Ecology and Society*, *15*(2), 27. https://doi.org/10.5751/ES-03305-150205

Ministry of Economy and Treasury. (n.d.). *Banco de Inversiones - invierte.pe*.

Ministry of Environment. (n.d.-a). *Geoservidor*. ZONIFICACIÓN ECOLÓGICA Y ECONÓMICA – ZEE. https://geoservidor.minam.gob.pe/zee-aprobadas/zee-aprobadas/

Ministry of Environment. (n.d.-b). *Mecanismos de retibucion por servicios ecosistemicos*. Retrieved October 4, 2019, from http://serviciosecosistemicos.minam.gob.pe/

Ministry of Environment. (2012). *Memoria descriptiva del mapa de cobertura vegetal del Peru*.

Ministry of Environment. (2014). *LA ESTRATEGIA NACIONAL DE DIVERSIDAD BIOLÓGICA AL 2021 Y SU PLAN DE ACCIÓN 2014-2018*.

Ministry of Environment. (2015a). *Mapa nacional de cobertura vegetal. Memoria descriptiva.* http://www.minam.gob.pe/patrimonio-natural/wp-content/uploads/sites/6/2013/10/MAPA-NACIONAL-DE-COBERTURA-VEGETAL-FINAL.compressed.pdf

Ministry of Environment. (2015b). *Mapa nacional de cobertura vegetal* (p. 1). Dirección General de Evaluación, Valoración y Financiamiento del Patrimonio Natural.

Ministry of Environment. (2017). *ESTADO SITUACIONAL DE LA ZONIFICACIÓN*

ECOLÓGICA Y ECONÓMICA (ZEE) A NIVEL REGIONAL.

Ministry of Environment. (2018). *Mapa nacional de ecosistemas del Perú. Memoria Descriptiva*.

Ministry of Environment, & SERNANP. (2016). *ÁREAS NATURALES PROTEGIDAS DEL PERÚ Conservación para el desarrollo sostenible*.

Miranda, A., Altamirano, A., Cayuela, L., Pincheira, F., & Lara, A. (2015). Different times, same story: Native forest loss and landscape homogenization in three physiographical areas of south-central of Chile. *Applied Geography*, *60*, 20–28. https://doi.org/10.1016/j.apgeog.2015.02.016

Molina, A., Vanacker, V., Brisson, E., Mora, D., & Balthazar, V. (2015). Multidecadal change in streamflow associated with anthropogenic disturbances in the tropical Andes. *Hydrology and Earth System Sciences*, *19*(10), 4201–4213. https://doi.org/10.5194/hess-19-4201-2015

Montoya-Tangarife, C., de la Barrera, F., Salazar, A., & Inostroza, L. (2017). Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaíso, Chile. *PLOS ONE*, *12*(11), e0188117. https://doi.org/10.1371/journal.pone.0188117

Mouchet, M. A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., & Lavorel, S. (2014). An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Global Environmental Change*, *28*(1), 298–308. https://doi.org/10.1016/j.gloenvcha.2014.07.012

Mulvaney, D., Robbins, P., & Freeman, C. P. (2012). Vegan. In *Green Food: An A-to-Z Guide* (p. 2). https://doi.org/10.4135/9781412971874.n145

Nakayama, T., Watanabe, M., Tanji, K., & Morioka, T. (2007). Effect of underground urban structures on eutrophic coastal environment. *Science of the Total Environment*, *373*(1), 270–288. https://doi.org/10.1016/j.scitotenv.2006.11.033

National Institute of Natural Resources. (2000). *Mapa forestal del Perú* (p. 1). INRENA.

Naturserve. (2009). *International Ecological Classification Standard: Terrestrial Ecological Classifications. Sistemas Ecológicos de los Andes del Norte y Centro*.

Nelson, G. C., Bennett, E., Berhe, A. A., Cassman, K., DeFries, R., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., Levy, M., Marco, D., Nakicenovic, N., O'Neill, B., Norgaard, R., Petschel-Held, G., Ojima, D., Pingali, P., Watson, R., & Zurek, M. (2006). Anthropogenic drivers of ecosystem change: An overview. In

Ecology and Society (Vol. 11, Issue 2, p. 29). https://doi.org/10.5751/ES-01826-110229

Oliveras, I., Girardin, C., Doughty, C. E., Cahuana, N., Arenas, C. E., Oliver, V., Huaraca Huasco, W., & Malhi, Y. (2014). Andean grasslands are as productive as tropical cloud forests. *Environmental Research Letters*, *9*(11), 115011. https://doi.org/10.1088/1748-9326/9/11/115011

Oscanoa, L., & Flores, E. (2016). INFLUENCIA DE TÉCNICAS DE MEJORA DE SUELOS SOBRE LA FUNCIÓN HÍDRICA DE PASTOS NATURALES ALTOANDINOS. *Ecología Aplicada*, *15*(2), 91. https://doi.org/10.21704/rea.v15i2.748

Pan, Y., Wu, J., & Xu, Z. (2014). Analysis of the tradeoffs between provisioning and regulating services from the perspective of varied share of net primary production in an alpine grassland ecosystem. *Ecological Complexity*, *17*(1), 79–86. https://doi.org/10.1016/j.ecocom.2013.11.001

Patton, M. (2002). *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*.

Pestalozzi, H. (2000). Sectoral Fallow Systems and the Management of Soil Fertility: The Rationality of Indigenous Knowledge in the High Andes of Bolivia. *Mountain Research and Development*, *20*(1), 64–71. https://doi.org/http://dx.doi.org/10.1659/0276-4741(2000)020[0064:SFSATM]2.0.CO;2

Petz, K., Alkemade, R., Bakkenes, M., Schulp, C. J. E., van der Velde, M., & Leemans, R. (2014). Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Global Environmental Change*, *29*, 223–234. https://doi.org/10.1016/j.gloenvcha.2014.08.007

Postigo, J. C. (2014). Perception and Resilience of Andean Populations Facing Climate Change. *Journal of Ethnobiology*, *34*(3), 383–400. https://doi.org/10.2993/0278-0771-34.3.383

Qiao, X., Gu, Y., Zou, C., Xu, D., Wang, L., Ye, X., Yang, Y., & Huang, X. (2019). Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. *Science of the Total Environment*, *651*, 218–229. https://doi.org/10.1016/j.scitotenv.2018.09.135

Queiroz, C., Meacham, M., Richter, K., Norström, A. V., Andersson, E., Norberg, J., & Peterson, G. (2015). Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. *Ambio*, *44*(1), 89–101. https://doi.org/10.1007/s13280-014-0601-0

Quintero-Gallego, M. E., Quintero-Angel, M., & Vila-Ortega, J. J. (2018). Exploring land use/land cover change and drivers in Andean mountains in Colombia: A case in rural Quindío. *Science of the Total Environment*, *634*, 1288–1299. https://doi.org/10.1016/j.scitotenv.2018.03.359

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. In *R Foundation for Statistical Computing* (Vol. 1, Issue 2.11.1, p. 409). https://doi.org/10.1007/978-3-540-74686-7

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J. E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., … Wagnon, P. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere*, *7*(1), 81–102. https://doi.org/10.5194/tc-7-81-2013

Raudsepp-Hearne, C, Peterson, G. D., & Bennett, E. M. (2010). Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences*, *107*(11), 5242–5247. https://doi.org/10.1073/pnas.0907284107

Raudsepp-Hearne, Ciara, & Peterson, G. D. (2016). Scale and ecosystem services: How do observation, management, and analysis shift with scale—lessons from Québec. *Ecology and Society*, *21*(3), art16. https://doi.org/10.5751/ES-08605-210316

Renard, D., Rhemtulla, J. M., & Bennett, E. M. (2015). Historical dynamics in ecosystem service bundles. *Proceedings of the National Academy of Sciences*, *112*(43), 13411–13416. https://doi.org/10.1073/pnas.1502565112

Restrepo, J. D., Kettner, A. J., & Syvitski, J. P. M. (2015). Recent deforestation causes rapid increase in river sediment load in the Colombian Andes. *Anthropocene*, *10*, 13–28. https://doi.org/10.1016/j.ancene.2015.09.001

Rieb, J. T., Chaplin-Kramer, R., Daily, G. C., Armsworth, P. R., Böhning-Gaese, K., Bonn, A., Cumming, G. S., Eigenbrod, F., Grimm, V., Jackson, B. M., Marques, A., Pattanayak, S. K., Pereira, H. M., Peterson, G. D., Ricketts, T. H., Robinson, B. E., Schröter, M., Schulte, L. A., Seppelt, R., … Bennett, E. M. (2017). When,

Where, and How Nature Matters for Ecosystem Services: Challenges for the Next Generation of Ecosystem Service Models. *BioScience*, *67*(9), 820–833. https://doi.org/10.1093/biosci/bix075

Roces-Díaz, J. V., Vayreda, J., Banqué-Casanovas, M., Díaz-Varela, E., Bonet, J. A., Brotons, L., De-Miguel, S., Herrando, S., & Martínez-Vilalta, J. (2018). The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships. *Science of the Total Environment*, *626*, 1270–1283. https://doi.org/10.1016/j.scitotenv.2018.01.150

Rodríguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., Dobson, A. P., & Peterson, G. D. (2006). Trade-offs across Space , Time , and Ecosystem Services. *Ecology and Society*, *11*(1). https://cals.arizona.edu/classes/ram696a/ES tradeoffs 2006.pdf

Rodríguez, L. C., Pascual, U., & Niemeyer, H. M. (2006). Local identification and valuation of ecosystem goods and services from Opuntia scrublands of Ayacucho, Peru. *Ecological Economics*, *57*(1), 30–44. https://doi.org/10.1016/J.ECOLECON.2005.03.022

Rolando, J. L., Dubeux, J. C., Perez, W., Ramirez, D. A., Turin, C., Ruiz-Moreno, M., Comerford, N. B., Mares, V., Garcia, S., & Quiroz, R. (2017). Soil organic carbon stocks and fractionation under different land uses in the Peruvian high-Andean Puna. *Geoderma*, *307*, 65–72. https://doi.org/10.1016/j.geoderma.2017.07.037

Rolando, J. L., Turin, C., Ramírez, D. A., Mares, V., Monerris, J., & Quiroz, R. (2017). Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes. In *Agriculture, Ecosystems and Environment* (Vol. 236, pp. 221–233). Elsevier. https://doi.org/10.1016/j.agee.2016.12.010

Rounsevell, M. D. A., Pedroli, B., Erb, K. H., Gramberger, M., Busck, A. G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M. J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P. H., & Wolfslehner, B. (2012). Challenges for land system science. *Land Use Policy*, *29*(4), 899–910. https://doi.org/10.1016/j.landusepol.2012.01.007

Rubiano, K., Clerici, N., Norden, N., & Etter, A. (2017). Secondary forest and shrubland dynamics in a highly transformed landscape in the Northern Andes of Colombia (1985-2015). *Forests*, *8*(6). https://doi.org/10.3390/f8060216

Saavedra Briones, P., & Sepúlveda-Varas, A. (2016). SYSTEMATIC TRANSITIONS IN LAND USE AND LAND COVER IN A PRE-ANDEAN SUB-WATERSHED WITH HIGH HUMAN INTERVENTION IN THE ARAUCANIA REGION, CHILE. *Ciencia e Investigación Agraria*, *43*(3), 6–6. https://doi.org/10.4067/s0718-16202016000300006

Saidi, N., & Spray, C. (2018). Ecosystem services bundles: Challenges and opportunities for implementation and further research. In *Environmental Research Letters* (Vol. 13, Issue 11, p. 113001). IOP Publishing. https://doi.org/10.1088/1748-9326/aae5e0

Salvador, F., Monerris, J., & Rochefort, L. (2014). Peatlands of the Peruvian Puna ecoregion: types, characteristics and disturbance. *Mires and Peat*, *15*(3), 1–17. http://www.mires-and-peat.net/,

Scholes, R. J., Reyers, B., Biggs, R., Spierenburg, M. J., & Duriappah, A. (2013). Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issue 1, pp. 16–25). Elsevier. https://doi.org/10.1016/j.cosust.2013.01.004

Scolozzi, R., Morri, E., & Santolini, R. (2012). Delphi-based change assessment in ecosystem service values to support strategic spatial planning in Italian landscapes. *Ecological Indicators*, *21*, 134–144. https://doi.org/10.1016/j.ecolind.2011.07.019

Segnini, A., Posadas, A., Quiroz, R., Milori, D. M. B. P., Saab, S. C., Neto, L. M., & Vaz, C. M. P. (2010). Spectroscopic Assessment of Soil Organic Matter in Wetlands from the High Andes. *Soil Science Society of America Journal*, *74*(6), 2246. https://doi.org/10.2136/sssaj2009.0445

SERFOR. (n.d.). *Plataforma de seguimiento de la Zonificación Forestal (v1.1)*. Retrieved September 6, 2019, from https://datastudio.google.com/u/0/reporting/1rBWIgdSv6bguI4RaAyMnpnW9myR3t-sB/page/qCMh

SERNANP. (2019). *ÁREAS NATURALES PROTEGIDAS DE ADMINISTRACIÓN NACIONAL CON CATEGORIA DEFINITIVA*.

Skarbø, K., & VanderMolen, K. (2016). Maize migration: key crop expands to higher altitudes under climate change in the Andes. *Climate and Development*, *8*(3), 245–255. https://doi.org/10.1080/17565529.2015.1034234

Sohel, M. S. I., Ahmed Mukul, S., & Burkhard, B. (2015). Landscape's capacities to supply ecosystem services in Bangladesh: A mapping assessment for Lawachara

National Park. *Ecosystem Services*, *12*, 128–135. https://doi.org/10.1016/j.ecoser.2014.11.015

Spake, R., Lasseur, R., Crouzat, E., Bullock, J. M., Lavorel, S., Parks, K. E., Schaafsma, M., Bennett, E. M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G. D., Schulp, C. J. E., Thuiller, W., Turner, M. G., Verburg, P. H., & Eigenbrod, F. (2017). Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. *Global Environmental Change*, *47*, 37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004

Stepputat, F., & Nyberg Sørensen, N. (2001). The rise and fall of "Internally Displaced People" in the Central Peruvian Andes. *Development and Change*, *32*(4), 769–791. https://doi.org/10.1111/1467-7660.00225

Stürck, J., & Verburg, P. H. (2017). Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. *Landscape Ecology*, *32*(3), 481–500. https://doi.org/10.1007/s10980-016-0459-6

Swinton, S. M., & Quiroz, R. (2003). Poverty and the deterioration of natural soil capital in the Peruvian altiplano. *Environment, Development and Sustainability*, *5*(3–4), 477–490. https://doi.org/10.1023/A:1025785231559

Tito, R., Vasconcelos, H. L., & Feeley, K. J. (2018). Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. *Global Change Biology*, *24*(2), e592–e602. https://doi.org/10.1111/gcb.13959

Tomscha, S. A., & Gergel, S. E. (2016). Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecology and Society*, *21*(1), art43. https://doi.org/10.5751/ES-08345-210143

Tovar, C., Seijmonsbergen, A. C., & Duivenvoorden, J. F. (2013). Monitoring land use and land cover change in mountain regions: An example in the Jalca grasslands of the Peruvian Andes. *Landscape and Urban Planning*, *112*(1), 40–49. https://doi.org/10.1016/j.landurbplan.2012.12.003

Trabucchi, M., Comín, F. A., & O'Farrell, P. J. (2013). Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services. *Regional Environmental Change*, *13*(4), 911–926. https://doi.org/10.1007/s10113-012-0392-4

Turner, B. L. (2002). Toward Integrated Land-Change Science: Advances in 1.5 Decades of Sustained International Research on Land-Use and Land-Cover

Change. In B. C. Steffen W., Jäger J., Carson D.J. (Ed.), *Challenges of a Changing Earth. Global Change — The IGBP Series* (pp. 21–26). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-19016-2_3

Turner, K. G., Odgaard, M. V., Bøcher, P. K., Dalgaard, T., & Svenning, J. C. (2014). Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landscape and Urban Planning*, *125*, 89–104. https://doi.org/10.1016/j.landurbplan.2014.02.007

Turner, M. G., O'Neill, R. V., Gardner, R. H., & Milne, B. T. (1989). Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecology*, *3*(3–4), 153–162. https://doi.org/10.1007/BF00131534

Vallet, A., Locatelli, B., Levrel, H., Wunder, S., Seppelt, R., Scholes, R. J., & Oszwald, J. (2018). Relationships Between Ecosystem Services: Comparing Methods for Assessing Tradeoffs and Synergies. *Ecological Economics*, *150*, 96–106. https://doi.org/10.1016/j.ecolecon.2018.04.002

Van Jaarsveld, A. S., Biggs, R., Scholes, R. J., Bohensky, E., Reyers, B., Lynam, T., Musvoto, C., & Fabricius, C. (2005). Measuring conditions and trends in ecosystem services at multiple scales: The Southern African Millennium Ecosystem Assessment (SAfMA) experience. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 425–441. https://doi.org/10.1098/rstb.2004.1594

Vásquez, E., Ladd, B., & Borchard, N. (2014). Carbon storage in a high-altitude Polylepis woodland in the Peruvian Andes. *Alpine Botany*, *124*(1), 71–75. https://doi.org/10.1007/s00035-014-0126-y

Verhagen, W., Van Teeffelen, A. J. A., Baggio Compagnucci, A., Poggio, L., Gimona, A., & Verburg, P. H. (2016). Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. *Landscape Ecology*, *31*(7), 1457–1479. https://doi.org/10.1007/s10980-016-0345-2

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., & Bradley, R. S. (2008). Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, *89*(3–4), 79–96. https://doi.org/10.1016/J.EARSCIREV.2008.04.002

Wei, H., Fan, W., Lu, N., Xu, Z., Liu, H., Chen, W., Ulgiati, S., Wang, X., & Dong, X. (2019). Integrating biophysical and sociocultural methods for identifying the relationships between ecosystem services and land use change: Insights from an

Oasis area. *Sustainability (Switzerland)*, *11*(9). https://doi.org/10.3390/su11092598

Wiegers, E. S., Hijmans, R. J., Herve, D., & Fresco, L. O. (1999). Land use intensification and disintensification in the Upper Canete valley, Peru. *Human Ecology*, *27*(2), 319–339. https://doi.org/10.1023/a:1018729428781

Wulder, M. A., Coops, N. C., Roy, D. P., White, J. C., & Hermosilla, T. (2018). Land cover 2.0. In *International Journal of Remote Sensing* (Vol. 39, Issue 12, pp. 4254–4284). https://doi.org/10.1080/01431161.2018.1452075

Xu, S., Liu, Y., Wang, X., & Zhang, G. (2017). Scale effect on spatial patterns of ecosystem services and associations among them in semi-arid area: A case study in Ningxia Hui Autonomous Region, China. *Science of the Total Environment*, *598*, 297–306. https://doi.org/10.1016/j.scitotenv.2017.04.009

Yang, G., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C., Du, Y., Fan, X., Ren, Y., & Chang, J. (2015). Using ecosystem service bundles to detect trade-offs and synergies across urban-rural complexes. *Landscape and Urban Planning*, *136*, 110–121. https://doi.org/10.1016/j.landurbplan.2014.12.006

Young, B. E., Young, K. R., & Josse, C. (2008). Vulnerability of Tropical Andean Ecosystems to Climate Change. *Climate Change and Biodiversity in the Tropical Andes*, 170–181.

Young, K. R. (2009). Andean land use and biodiversity: Humanized landscapes in a time of change. *Annals of the Missouri Botanical Garden*, *96*(3), 492–507. https://doi.org/10.3417/2008035

Young, K. R. (2014). Ecology of land cover change in glaciated tropical mountains. *Revista Peruana de Biologia*, *21*(3), 259–270. https://doi.org/10.15381/rpb.v21i3.10900

Zen, M., Candiago, S., Schirpke, U., Egarter Vigl, L., & Giupponi, C. (2019). Upscaling ecosystem service maps to administrative levels: beyond scale mismatches. *Science of the Total Environment*, *660*, 1565–1575. https://doi.org/10.1016/j.scitotenv.2019.01.087

Zheng, Z., Fu, B., Hu, H., & Sun, G. (2014). A method to identify the variable ecosystem services relationship across time: a case study on Yanhe Basin, China. *Landscape Ecology*, *29*(10), 1689–1696. https://doi.org/10.1007/s10980-014-0088-x

Zimmermann, M., Meir, P., Silman, M. R., Fedders, A., Gibbon, A., Malhi, Y., Urrego, D. H., Bush, M. B., Feeley, K. J., Garcia, K. C., Dargie, G. C., Farfan, W. R.,

Goetz, B. P., Johnson, W. T., Kline, K. M., Modi, A. T., Rurau, N. M. Q., Staudt, B. T., & Zamora, F. (2010). No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes. *Ecosystems*, *13*(1), 62–74. https://doi.org/10.1007/s10021-009-9300-2

APPENDIX I. ARTICLES AND BOOK CHAPTER PUBLISHED

ARTICLE

UNDERSTANDING LAND USE CHANGES IN THE CENTRAL HIGH-ANDEAN MOIST PUNA

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ABSTRACT

Mountain ecosystems around the world are facing rapid land-cover changes, that have received much attention among scientists, managers, and policy-makers. A growing scientific production has been possible by free and open access data and the use of remote sensing and geographic information system tools. In this context, our study quantified the land-use changes across 25 provinces in the central high-Andean moist Puna over the interval of 13 years, using a selection of eleven land use/cover types included in the standardized nomenclature of the Corine Land Cover for Peru. Thereafter, we determine the importance of social-economic driving factors in two-time periods, from 2000 to 2009 and 2009 to 2013. The results described three spatial patterns: (1) a North – South division (2) two different trends described by intensification/de-intensification agriculture, and (3) a persistent forestland deterioration. Overall, our study reveals that agriculture in densely occupied provinces was the leading land-use change process negatively affecting pasture and forest extent. Moreover, this research ratifies that the understanding of the spatial patterns of changes and their relationships with explanatory variables can clarify land-use change trajectories. We hope our study will support spatial decision-making in complex mountain landscapes.

Keywords: land use change, mountain ecosystem, agricultural systems, spatial planning, GIS, high-Andean Puna, Peru

1. Introduction

The most important human induced environmental impacts have become recognized as a consequence of changes in land-cover and land-use (B. L. Turner, 2002). These rapid land-cover changes occurred around the world have received much attention from scientists and there were numerous studies focused on various research issues at different spatial scales (Du et al., 2014; Egarter Vigl et al., 2017; Kuemmerle et al., 2016; E. Lee et al., 2018). This growing scientific production has been possible by free and open access data (Wulder et al., 2018) and the use of remote sensing and geographic information system (GIS) tools (Lu et al., 2004). GIS provides a flexible environment for a rapidly developing data processing and analysing for change detection in a study area.

In high-Andean mountains, most previous land-use change studies using GIS have focused on a peri-urban interface (Haller, 2012; Rubiano et al., 2017), or a watershed (Anselm et al., 2018; Gutiérrez B. et al., 2013; Molina et al., 2015; Restrepo et al., 2015; Saavedra Briones & Sepúlveda-Varas, 2016), or a specific ecosystem (Ektvedt et al., 2012; Miranda et al., 2015; Quintero-Gallego et al., 2018; Tovar et al., 2013). To the best of our knowledge, there are no land-use change studies at provincial scale across high-Andean highlands. In Peru, land planning at local level is regulated by provincial municipalities (Organic Law of Municipalities No. 27972, 27 of May of 2003), these could benefit from land-use research and improve management purposes and decision-making.

In this context, this paper is focusing in a sector of the Peruvian high-Andean mountains, the central moist Puna (64,025 km^2), comprised within the administrative boundaries of 25 provinces in the departments of Junín, Huancavelica and Ayacucho (Fig 1). Provincial area ranged from 724 to 10,999 km^2 with an average of 2561 km^2. These provinces define a highly populated mountain ecosystem (population at the end

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of 2017 was 2 096,156 (INEI - National Institute of Statistics and Informatics, n.d.-b)) that has been occupied and its resources profited during several millennia by Andean civilizations (Josse, Cuesta, Navarro, Barrena, Cabrera, Chacón-Moreno, et al., 2009; K. R. Young, 2009). Its main social-ecosystems consist of natural grassland, shrubland and agricultural areas (K. R. Young, 2009), that are threatened by human activities (MA, 2005), as agricultural intensification, grasslands extent, afforestation and urbanization (Lambin et al., 2003; Madrigal-Martínez & Miralles i García, 2019b).

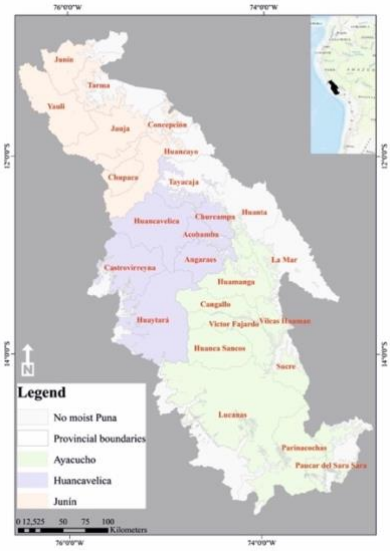

Figure 1. Central high-Andean moist Puna.

The study quantified the land-use changes at provincial scale across the central high-Andean moist Puna over the interval of 13 years, from 2000 to 2013, using a selection of eleven land use/cover (LULC) types included in the standardized nomenclature of the Corine Land Cover (CLC) for Peru. The LULC units include two classes related to artificial surface (continuous urban fabric and mineral extraction sites), one-unit match to agricultural areas, seven attributes associated to forests and semi-natural areas (low forest, forest plantation, natural grassland, shrublands, bare rock, sparsely vegetated areas and glaciers), one item linked to wetlands (peatbogs and high-Andean wetlands) and, finally, two categories linked to water bodies (water courses and water bodies). In a second step, we determine the importance of social-economic driving factors in two-time periods, from 2000 to 2009 and 2009 to 2013. The factors considered were related to population growth, economic development and technological progress.

Finally, the work detailed in this paper address the first objective of a PhD thesis and resolve the following aim questions: (1) Which are the main anthropogenic land-use changes? (2) Which are the significant social-economic drivers that explain land-use changes? We hope our results will support spatial decision-making in the high-Andean region. In addition, our findings can provide a reference for studies in complex mountain landscapes.

2. Methods

2.1. Identification of land use/cover units

The identification of the 11 representative high-Andean moist Puna LULC units included in the standardized nomenclature of the Corine Land Cover (CLC) for Peru was achieved from three sources, the map of high-Andean ecosystems from 2000

(Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009b), the official flora cover map from 2009 (Ministry of Environment, 2012) and the official flora cover map from 2013 (Ministry of Environment, 2015a). These are polygon shapefiles generated in a mapping scale of 1:100,000 with Landsat (TM) images. Table 1 shows the harmonization of the three-time step features to obtain the moist Puna LULC units.

Table 1. Land use/cover units resulting from the features of the three-time step data

CLC code	LULC units	Features	Data Source
1.1.1.	Continuous urban fabric	• Cities and settlements	(1) (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009b)
		• Urban area	(2)(Ministry of Environment, 2012); (3)(Ministry of Environment, 2015a)
2.	Agricultural areas	• Human at work areas	(1)
		• Crops	(2)
		• Andean agriculture	(3)
3.1.1.	Low forest	• Inter-Andean xeric montane forest and shrublands • Low high-Andean forest • High-montane low forest and shrublands	(1)
		• Queñoal • Inter-Andean xeric forest	(2)
		• Inter-Andean xeric forest • High-Andean relict forest • Meso-Andean relict forest	(3)
3.2.	Forest plantation	• Human at work areas	(1)
		• Afforestation	(2)
		• Forest plantation (pinus and eucalyptus species)	(3)
3.3.1.	Natural grassland	• High-Andean grassland • High-montane grassland	(4)(National Institute of Natural Resources, 2000); (3)
		• High-Andean grassland • Puna grass	(2)
3.3.2.	Shrublands	• Inter-Andean xeric montane shrublands • Inter-Andean xeric shrublands • High-montane shrublands • High-Andean shrublands	(1)
		• Shrublands	(2); (3)
3.4.3.	Sparsely vegetated areas	• Tundra	(4); (2)
		• High-Andean areas with rare vegetation	(2); (3)
3.4.5.	Glaciers	• Nival	(1)
		• Glaciers	(2); (3)
4.1.2.	Peatbogs and high-Andean wetlands	• High-Andean wetlands	(1); (2); (3)
5.1.1.	Water courses	• Water bodies	(1)
		• River	(2); (3)
5.1.2.	Water bodies	• Water bodies	(1)
		• Lagoons and lakes	(2); (3)

Some limitations were detected in the map of high-Andean ecosystems. It has a vague delimitation for two land units (agricultural areas and forest plantation) comprehending them in only one land-use category (human at work areas). This limitation was clarified using the detailed land-use types from the two official flora cover maps. Another constraint was found in natural grassland and sparsely vegetated areas, these were better defined when utilised the data from the official Peruvian forest map (National Institute of Natural Resources, 2000)

2.2. Analysing spatial land-use change in the central moist Puna

Land-use changes between 2000 and 2013 were calculated by means of a transition matrix obtained after using ArcGIS 10.3 (ESRI, 2014). The matrices of land-use transition were established for two-time periods, including 2000–2009 and 2009–2013. Each transition matrix gathered the quantity of land that was converted from each LULC unit to any other or units that remain unchanged in the study periods. Changes of interest in this study were related to agricultural areas, grassland extent and forestland size. These variations were further calculated obtaining increased/decreased extents. Next, to measure and compare the intensity of land-use changes between provinces, proportion of area increase and extent decrease (of the chosen classes) were calculated for the two-time periods. The following formula was used to calculate the index for area increase (1) and for area decrease (2):

$$Pi_n = \frac{LULC_{nt2}}{AT_n} \quad (1)$$

$$Pd_n = \frac{(LULC_{nt2})_{nt1} - LULC_{nt1}}{AT_n} \quad (2)$$

where $LULC_{nt2}$ is the new area (km^2) of the chosen class in a province *n* at the final year *t2;* $(LULC_{nt2})_{nt1}$ is the overlapping area of a given class in both years; $LULC_{nt1}$ is the area (km^2) of the chosen class in a province *n* at the initial year *t1*; AT_n is the total area of the province *n*.

This index gave a relative measure of the change that was ranked in five levels of equal intervals representing the intensity of expansion/contraction of each chosen class at provincial scale. Furthermore, we performed Pearson's correlation (r_p) to assess the pairwise relations between LULC categories for the two-time periods at provincial scale, using R (R Development Core Team, 2016).

2.3. Determining the explanatory capacity of social-economic drivers

Redundancy analysis (RDA) was computed to determine the importance and capacity of social-economic drivers for predicting the land-use changes during the two-time periods. RDA was calculated using the "vegan" R package and the function "ordistep" (R Development Core Team, 2016), after 10,000 permutations (Legendre, 2018). The drivers considered were related to population growth, economic development and technological progress (Table 2). These variables were selected due to their role as anthropogenic drivers of ecosystem change (Nelson et al., 2006) and data availability. Information from public census statistics (INEI - National Institute of Statistics and Informatics, n.d.-b) were used to quantify each variable.

Table 2. Factors, specific drivers and proxies used for predicting land-use changes

Factor	Driver	Proxy	Unit

Population growth	Population density	Log average of population density (for each period)	People/km²
Economic development	Income	Net annual income per family (averaged for each period)	S/year
Technological progress	Education	Population with completed secondary school education (averaged for each period)	%

3. Results

3.1. Changes in the extent of land use/cover categories

Figure 2A shows the spatial distribution of LULC categories across central Moist Puna from 2000 to 2013. The dominant category is natural grassland that is spatially dispersed covering more than 60% of the territory in each year (Fig 2B). The second major LULC type was shrubland, covering more than 15% of the entire area in each year, and mainly located in the south-west it exhibited a transitional zone between the moist Puna and the Peruvian Pacific desert. The third major LULC type was agricultural area with 8% of the landscape in 2000 and top with 12% in 2009, mostly associated to the provinces that form Mantaro watershed. Sparsely vegetated areas and high-Andean wetlands occupied around 6% of the territory each year, covering central and northern areas. Low forest extent reduced from 3% to 1% during the time period, showing a slight aggregation effect with cropland extent. Water bodies and glaciers (only in 2000) represent 1% of the landscape, this last category is spatially associated with sparsely vegetated areas. There were only small amounts of urban lands, forest plantations and water courses covering less than 1% separately.

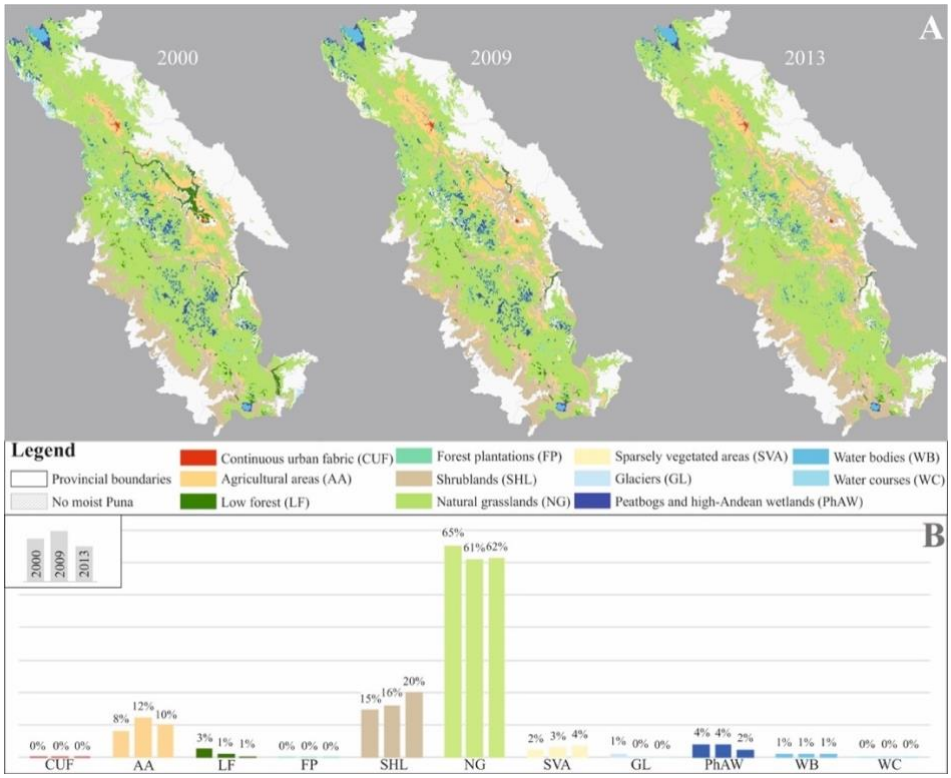

Figure 2. (A) Spatial distribution of land use/cover categories and (B) barplots showing the proportion of land of each category, in central moist Puna across time

Table 3 presents the transition matrix between 2000 and 2009 in central Moist Puna. The overall agreement (percentage of coinciding area, under equal LULC class)

among the comparative maps was 92%. Of the 8% of land-use change, 4.2% disturbed the chosen LULC categories. Agricultural areas increased by about 53.1%, mainly as a result of the encroachment of natural grasslands and shrublands in that order, whereas had a reduction of 233.6 km^2 after land abandonment. Low forest reduced by 60.2%, largely replaced by shrublands following a forest degradation process, whereas experimented a slight recovery process (20.8 km^2) due to colonisation of shrublands and agricultural land. Natural grasslands decreased around 2700 km^2 principally by expanding agricultural frontier, but had a minor augmented due to glaciers retreat and dried up of high-Andean wetlands (108 km^2).

Table 3. Transition matrix showing land-use changes of interest (in square kilometres) and change ratio occurred between 2000 and 2009 in central Moist Puna

2009 / 2000	2.	3.1.1.	3.3.1.	Other	Total	Change (%)*
2.	4881.4	16.3	2400	556.2	**7853.9**	53.1
3.1.1.	10.6	677.5	4.4	10.2	**702.7**	-60.2
3.3.1.	233.6	2.1	38656.9	108	**39006**	-6.6
Other	4.3	1069	693.8	14701.2	**16468.3**	7.1
Total	**5129.9**	**1764.9**	**41755.1**	**15375.6**	**64025.5**	

CLC Code: 2. Agricultural areas; 3.1.1. Low forest; 3.3.1. Natural grasslands. * Change ratio between years was calculated as (($Area_i$ in 2009 – $Area_i$ in 2000)/$Area_i$ in 2000) x 100, where $Area_i$ = area of each land use/cover class.

Table 4 introduces the transition matrix between 2009 and 2013 in central Moist Puna. The overall agreement among the comparative maps was 91.8%. Of the 8.2% of land-use change, 2% (1317 km^2) disturbed the chosen LULC categories. Agricultural extent decreased by about 17.7%, mainly as a result of land abandonment (2099.4 km^2), whereas had a growth of 542 km^2 at the expenses of grassland. Low forest (reduced by 47.5%) continued under a degradation process also identified in the preceding time period. Natural grasslands increased by 0.8% (300 km^2) principally by farming de-intensification and the persistent dried up process of high-Andean wetlands.

Table 4. Transition matrix showing land-use changes of interest (in square kilometres) and change ratio occurred between 2009 and 2013 in central Moist Puna

2013 / 2009	2.	3.1.1.	3.3.1.	Other	Total	Change (%)*
2.	5754.2	8.1	542	160.5	**6464.8**	-17.7
3.1.1.	0	369.1	0	0	**369.1**	-47.5
3.3.1.	599.4	168	37457.8	1081.3	**39306.5**	0.8
Other	1500.3	157.5	1006.2	15221.1	**17885.1**	8.7
Total	**7853.9**	**702.7**	**39006**	**16462.9**	**64025.5**	

CLC Code: 2. Agricultural areas; 3.1.1. Low forest; 3.3.1. Natural grasslands. * Change ratio between years was calculated as (($Area_i$ in 2013 – $Area_i$ in 2009)/$Area_i$ in 2009) x 100, where $Area_i$ = area of each land use/cover class.

Fig. 3 on the top row illustrates the intensity of land increase/decrease from 2000 to 2009 across the 25 provinces in central moist Puna. In this initial-time period, central moist Puna described a territory with a tendency to increase cropland areas and to decrease pasture and forestland extents. There are six provinces with a high intensity level and twelve with medium strength level, affected by agricultural area increase, pasture area decrease and forest extent decline. However, most of the provinces had very low proportion of change (32%) or no change (41%) denoting

undisturbed areas primarily related to cropland extent decrease, grassland area increases and forestland extent increase.

At LULC category level, spatial distribution shows that increase in cropland extent (Fig. 3a) was related to decrease in pasture area (Fig 3d), validated by a strong negative correlation (r_p= -0.96839901 and P-value <0.001). In the same way, reduction of agricultural areas (Fig. 3b) corresponded with the expansion of pasture lands (Fig. 3c) proving a negative relationship (r_p= -0.6321261 and P-value <0.001). Forestland extent increase (Fig. 3e) occurred with slight force (1.8% of proportion of land-change) in one province (Churcampa), whereas forest area decreased (Fig. 3f) in 12 provinces (half of the territory), but intensely focussed in four jurisdictions. Pairwise relation between goals and losses of forest class presented a moderate negative correlation (r_p= -0.4194168 and P-value <0.05). Whereas very slight negative relation was found between forestland decrease and crops increase (r_p= -0.3497234 and P-value <0.1), even so, two strongly deforested provinces (19% for Acobamba and 8.3% for Angaraes) developed an important growth of farming activity (15% for Acobamba and 9.4% for Angaraes).

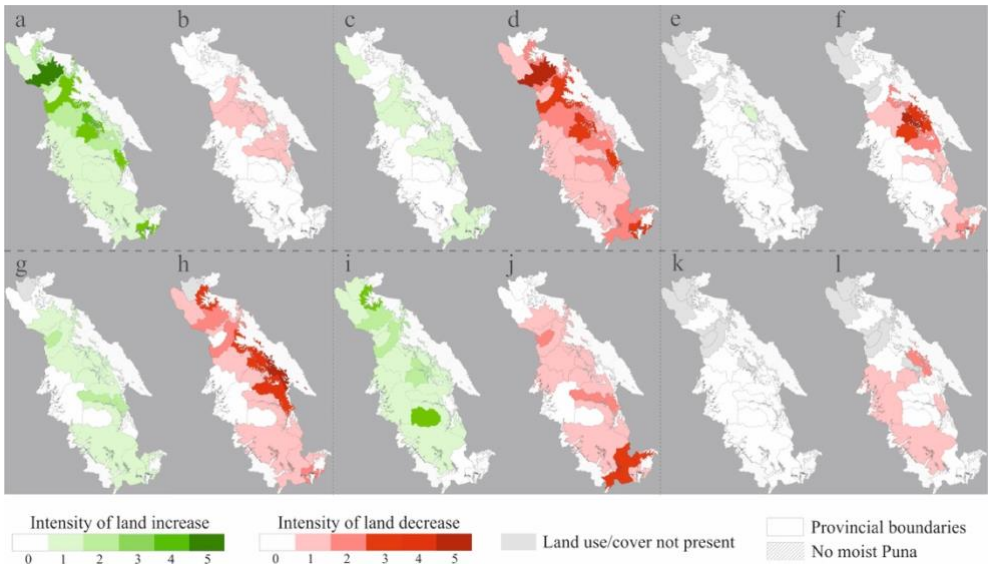

Figure 3. Land increase/decrease intensity of the chosen land use/cover categories at provincial scale in central Moist Puna. Top row: maps for the period 2000 and 2009. Bottom row: maps for the period 2009 and 2013. Agricultural area: a, b, g, h; Natural grassland extent: c, d, i, j; Forestland extent: e, f, k, l. Ranks of intensity: 0 (no change), 1 (|>0% – 3.8%|), 2 (|>3.8% – 7.6%|), 3 (|>7.6% – 11.4%|), 4 (|>11.4% – 15.2%|), 5 (|>15.2% – 19.0%|)

Fig. 3 on the bottom row shows the intensity of land increase/decrease from 2009 to 2013 across the 25 provinces in central moist Puna. In this final-time period, forestland extent continued declining, grassland extent stayed balanced and agricultural areas inclined negatively. Despite this land-use changes, the territory continued, as initial-time period, dominated by areas with very low proportion of change (39% of the provinces) or with no change (33% of the provinces). However, there were strong variations registered in eight provinces due to cropland extent decrease.

At LULC category level, Fig. 3g and Fig. 3j captured similar spatial distribution between provinces affected by cropland extent increase and pasture area decrease, confirming a negative correlation (r_p= -0.5596783 and P-value <0.01). On the contrary, as can be seen from the Fig. 3i and Fig. 3h, enlargement of grassland extent had no significant relation (r_p= -0.0352285 and P-value= 0.8672) with reduction of agricultural areas. Whereas forestland extent declined (Fig. 3l) with very low intensity in seven provinces that were positively interrelated to cropland size decrease (r_p= 0.4883865 and P-value <0.05). It should be noted that no forest area increase was assessed in the final period (Fig. 3k).

3.2. Capacity and importance of drivers to predict the distribution of individual land-use changes

Each explanatory variable displayed different spatial distribution within the study area (Fig. 4). Population density varied slightly between both periods, characterising a territory with eleven provinces in a growing rate and fifteen provinces with a declining proportion over time. Income driver showed rather similar values for all the provinces, except for three provinces, Huamanga and Huancayo that include a major city each, and Yauli characterised by mining development. Education presented provinces of Junin with a higher percentage of people with completed secondary school than the provinces of Ayacucho and Huancavelica.

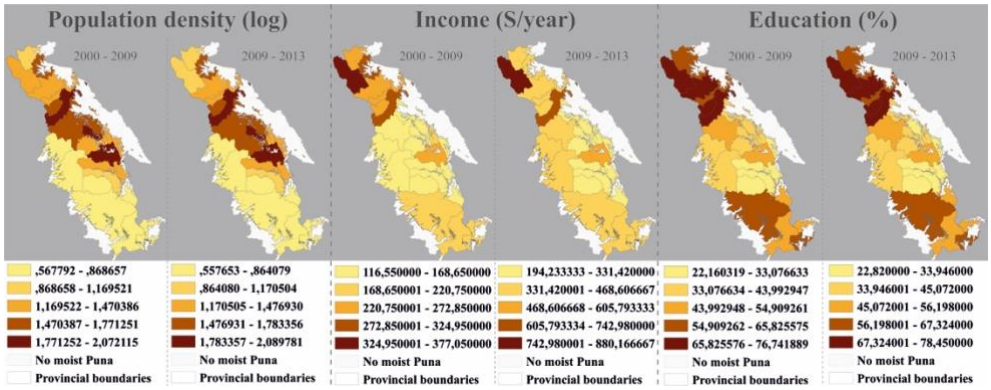

Figure 4. Spatial distribution of each driver for both time periods. The values of drivers are organised in equal interval quintiles.

There were disparities regarding how well the drivers predicted individual land-use changes (Fig. 5A). Changes in area decrease were better predicted in agricultural area (both periods), forestland extent (2000-2009) and natural grassland extent (2000-2009), in that order. Natural grassland decrease (2009-2013), forestland extent decrease (2009-2013) and all changes in area increase were poorly predicted by all three drivers. Overall, our results show that variations of cropland extent were the best explained.

The function “ordistep” of redundancy analysis showed that the significance to predict land-use changes was shared among variables, and that different land-use changes were best predicted by different variables (Fig. 5B). Population density was the best driver showing its importance for predicting cropland area changes (both periods), forestland and pasture extent decrease (2000-2009). Income did well predict forestland extent decrease during 2000-2009, and education did well explain agricultural area decrease in both time-steps. No variables predicted natural grassland

decrease (2009-2013) and increase (both periods), forestland extent decrease (2009-2013) and increase (2000-2009). Overall, drivers had best significance clarifying changes in the first-time period.

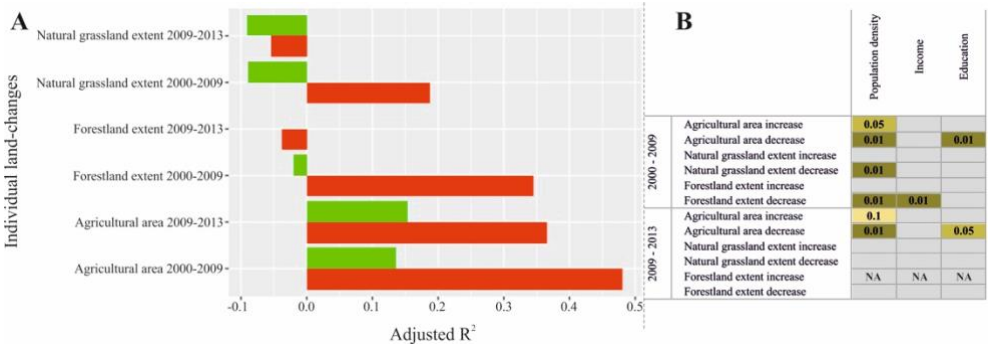

Figure 5. (A) Capacity of drivers to predict the distribution of individual land-use changes for the two-time periods (green horizontal barplots are relate to LULC area increase; red horizontal barplots are relate to LULC area decrease) (B) Importance of each driver for predicting individual land-changes for the two-time periods (boxes with P-value of significant relationship are coloured; darker colours indicate a strong correlation; grey boxes indicate no significance; NA indicates not available)

4. Discussion and Conclusion

This study analysed spatial patterns of land-use change occasioned by human activities in central high-Andean moist Puna since 2000. The results described three patterns: (1) a North – South division in terms of land-use change intensity over time, (2) two spatially different trends of intensifying agriculture during 2000-2009 and de-intensification during 2009-2013, negatively correlated to natural grassland extent, and (3) a persistent negative trend of forestland area over time and across space. Moreover, the observed land-use change trends were predicted by explanatory variables based on publicly available data.

The first spatial pattern identified a North - South divide in terms of land-use change intensity that was primarily related to population growth factor (Figures 4 and 5B). Northern side of the moist Puna was characterised by high intensity levels of land increase/decrease in each chosen LULC type (Fig. 3). Most of these provinces are located in the Mantaro river basin characterised by fertile lowlands and high population density (especially in the surrounding areas of the two major cities, Huancayo and Ayacucho). On the contrary, the South sector represented by larger desolate highland extents showed a prevalent very low proportion of area change (Fig. 3). These results agree with similar findings in the Andes that remarked the driven role of high population density predicting agricultural intensification (Caycho-Ronco et al., 2009; Haller, 2012), while isolated rural communities have little motivation to advance in their land beyond subsistence farming (Swinton & Quiroz, 2003).

The second important pattern assessed in central high-Andean moist Puna was described by two trajectories concerning cropland extent. The first trend described a process of agricultural expansion predicted by population growth during 2000-2009 (Figures 3a and 4). This period was characterised by an internal migration highly occurred in the Mantaro Valley's that promoted the rapid growth of commercial farming in the lowlands (Haller & Borsdorf, 2013; Stepputat & Nyberg Sørensen, 2001). Whereas, the second trend showed farming land decrease during 2009-2013 linked to

high population density and low schooling percentage (Fig. 5B). Fonte et al. (Fonte et al., 2012) and Skarbø and Van der Molen (Skarbø & VanderMolen, 2016) confirmed that population increase result in soil degradation pushing farmers to crop higher elevations with more favourable conditions. In the same way, Agudelo-Patiño and Miralles-Garcia (Agudelo-Patiño & Miralles i Garcia, 2015) reported that the city growth shifted agricultural peri-urban systems in an Andean metropolitan area.

The third spatial pattern showed a trajectory of forestland extent decrease over the two-time steps and across half of provinces in the central moist Puna primarily defined by high population density, low family income and education (Fig. 4). Forest area degraded (replaced by shrublands) more intensely during 2000-2009 (Fig. 3f), mainly caused by overgrazing and controlled burning, which are principal drivers assessed in previous work (Fjeldså, 2002; Hosonuma et al., 2012; Josse, Cuesta, Navarro, Barrena, Cabrera, Chacón-Moreno, et al., 2009). Although deforestation provinces were correlated to agricultural expansion, not represented an important process, contrary to global study findings (Geist & Lambin, 2002; Hosonuma et al., 2012). On the other hand, during 2009-2013, few provinces had a forest decline not well explained by low population density and middle percentage of adults with complete secondary school.

In that sense, although our research focused on causal factors of the land-use change, there is a lack for explaining the observed spatial patterns that suggest further assessment. However, we presented a transparent approach about spatial patterns of land-use changes in in the moist Puna that can contribute to a better understanding of complex social-ecological mountain landscapes. Understanding the spatial patterns of changes in the extent and their explanatory variables, is important for clarifying land-use change trajectories. Therefore, typifying land-use change dynamics of the moist Puna would be a beneficial and interesting field for future research. Moreover, our study could be used as starting point for the development of research focusing on the impact of the land-use change patterns on biodiversity and ecosystem services.

REFERENCES

Abson, D. J., von Wehrden, H., Baumgärtner, S., Fischer, J., Hanspach, J., Härdtle, W., Heinrichs, H., Klein, A. M., Lang, D. J., Martens, P., & Walmsley, D. (2014). Ecosystem services as a boundary object for sustainability. *Ecological Economics*, *103*, 29–37. https://doi.org/10.1016/j.ecolecon.2014.04.012

Affek, A. N., & Kowalska, A. (2017). Ecosystem potentials to provide services in the view of direct users. *Ecosystem Services*, *26*, 183–196. https://doi.org/10.1016/j.ecoser.2017.06.017

Agudelo-Patiño, L. C., & Miralles i Garcia, J. L. (2015). Design and management of the metropolitan green belt of Aburrá Valley, Colombia. *The Sustainable City X*, *1*, 193–203. https://doi.org/10.2495/sc150181

Aguilera, J., Motavalli, P., Valdivia, C., & Gonzales, M. A. (2013). Impacts of Cultivation and Fallow Length on Soil Carbon and Nitrogen Availability in the Bolivian Andean Highland Region. *Mountain Research and Development*, *33*(4), 391–403. https://doi.org/10.1659/MRD-JOURNAL-D-12-00077.1

Aide, T. M., Clark, M. L., Grau, H. R., López-Carr, D., Levy, M. A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M. J., & Muñiz, M. (2013). Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). *Biotropica*, *45*(2), 262–271. https://doi.org/10.1111/j.1744-7429.2012.00908.x

Aide, T. M., & Grau, H. R. (2004). Globalization, migration, and latin american

ecosystems. In *Science* (Vol. 305, Issue 5692, pp. 1915–1916). https://doi.org/10.1126/science.1103179

Albert, C., Aronson, J., Fürst, C., & Opdam, P. (2014, October 10). Integrating ecosystem services in landscape planning: requirements, approaches, and impacts. *Landscape Ecology*, *29*(8), 1277–1285. https://doi.org/10.1007/s10980-014-0085-0

Anselm, N., Brokamp, G., & Schütt, B. (2018). Assessment of Land Cover Change in Peri-Urban High Andean Environments South of Bogotá, Colombia. *Land*, *7*(2), 75. https://doi.org/10.3390/land7020075

Balthazar, V., Vanacker, V., Molina, A., & Lambin, E. F. (2015). Impacts of forest cover change on ecosystem services in high Andean mountains. *Ecological Indicators*, *48*, 63–75. https://doi.org/10.1016/j.ecolind.2014.07.043

Baraer, M., Mckenzie, J. M., Mark, B. G., Bury, J., & Knox, S. (2009). Characterizing contributions of glacier melt and groundwater during the dry season in a poorly gauged catchment of the Cordillera Blanca (Peru). In *Adv. Geosci* (Vol. 22). www.adv-geosci.net/22/41/2009/

Bhandari, P., KC, M., Shrestha, S., Aryal, A., & Shrestha, U. B. (2016). Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal. *Applied Geography*, *69*, 25–34. https://doi.org/10.1016/j.apgeog.2016.02.003

Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Früh-Müller, A., Machnikowski, F., Mader, V. L., Nilsson, L., Sasaki, K., Rundlöf, M., Wolters, V., & Smith, H. G. (2015). Ecosystem services-current challenges and opportunities for ecological research. *Frontiers in Ecology and Evolution*, *2*(JAN). https://doi.org/10.3389/fevo.2014.00087

Blancas, A. N. I., Torre-Cuadros, M. de los Á. La, & Carrera, G. A. M. (2018). Using Foresight to Gain a Local Perspective on the Future of Ecosystem Services in a Mountain Protected Area in Peru. *Mountain Research and Development*, *38*(3), 192–202. https://doi.org/10.1659/mrd-journal-d-17-00090.1

Boillat, S., Scarpa, F. M., Robson, J. P., Gasparri, I., Aide, T. M., Aguiar, A. P. D., Anderson, L. O., Batistella, M., Fonseca, M. G., Futemma, C., Grau, H. R., Mathez-Stiefel, S. L., Metzger, J. P., Ometto, J. P. H. B., Pedlowski, M. A., Perz, S. G., Robiglio, V., Soler, L., Vieira, I., & Brondizio, E. S. (2017). Land system science in Latin America: challenges and perspectives. In *Current Opinion in Environmental Sustainability* (Vols. 26–27, pp. 37–46). Elsevier. https://doi.org/10.1016/j.cosust.2017.01.015

Bolliger, J., & Mladenoff, D. J. (2005). Quantifying spatial classification uncertainties of the historical Wisconsin landscape (USA). *Ecography*, *28*(2), 141–156. https://doi.org/10.1111/j.0906-7590.2005.03955.x

Brandt, J. S., & Townsend, P. A. (2006). Land use - Land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. *Landscape Ecology*, *21*(4), 607–623. https://doi.org/10.1007/s10980-005-4120-z

Burkhard, B., Kandziora, M., Hou, Y., & Müller, F. (2014). Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landscape Online*, *34*(1), 1–32. https://doi.org/10.3097/LO.201434

Burkhard, B., Kroll, F., Müller, F., & Windhorst, W. (2009). Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments.

Landscape Online, *15*(1), 1–22. https://doi.org/10.3097/LO.200915
Burkhard, B., Kroll, F., Nedkov, S., & Müller, F. (2012). Mapping ecosystem service supply, demand and budgets. *Ecological Indicators*, *21*, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019
Campagne, C. S., Roche, P., Gosselin, F., Tschanz, L., & Tatoni, T. (2017). Expert-based ecosystem services capacity matrices: Dealing with scoring variability. *Ecological Indicators*, *79*, 63–72. https://doi.org/10.1016/j.ecolind.2017.03.043
Caycho-Ronco, J., Arias-Mesia, A., Oswald, A., Esprella-Elias, R., Rivera, A., F. Yumisaca, J., & Andrade-Piedra. (2009). Tecnologías sostenibles y su uso en la producción de papa en la región altoandina. *Revista Latinoamericana de La Papa*, *15*(1), 20–37.
Charrad, M., Ghazzali, N., Boiteau, V., & Maintainer, A. N. (2015). *NbClust Package for determining the best number of clusters*. https://cran.r-project.org/web/packages/NbClust/NbClust.pdf
Cochi Machaca, N., Condori, B., Pardo, A. R., Anthelme, F., Meneses, R. I., Weeda, C. E., & Perotto-Baldivieso, H. L. (2018). Effects of grazing pressure on plant species composition and water presence on bofedales in the Andes mountain range of Bolivia. *Mires and Peat*, *21*(15), 1–15. https://doi.org/10.19189/MaP.2017.OMB.303
Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10.1177/001316446002000104
Cord, A. F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., & Volk, M. (2017). Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. In *Ecosystem Services* (Vol. 28, pp. 264–272). Elsevier. https://doi.org/10.1016/j.ecoser.2017.07.012
Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F., Verkerk, P. J., & Lavorel, S. (2015). Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. *Journal of Applied Ecology*, *52*(5), 1145–1155. https://doi.org/10.1111/1365-2664.12502
Cui, F., Tang, H., Zhang, Q., Wang, B., & Dai, L. (2019). Integrating ecosystem services supply and demand into optimized management at different scales: A case study in Hulunbuir, China. *Ecosystem Services*, *39*. https://doi.org/10.1016/j.ecoser.2019.100984
Custodio, M., Chanamé, F., Pizarro, S., & Cruz, D. (2018). Quality of the aquatic environment and diversity of benthic macroinvertebrates of high Andean wetlands of the Junín region, Peru. *The Egyptian Journal of Aquatic Research*, *44*(3), 195–202. https://doi.org/10.1016/J.EJAR.2018.08.004
Dade, M. C., Mitchell, M. G. E., McAlpine, C. A., & Rhodes, J. R. (2019). Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. In *Ambio* (Vol. 48, Issue 10, pp. 1116–1128). Springer Netherlands. https://doi.org/10.1007/s13280-018-1127-7
de Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*(3), 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

de Gruijter, J. J., Bierkens, M. F. P., Brus, D. J., & Knotters, M. (2006). Sampling for Natural Resource Monitoring. In *Sampling for Natural Resource Monitoring*. Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-33161-1

de Valença, A. W., Vanek, S. J., Meza, K., Ccanto, R., Olivera, E., Scurrah, M., Lantinga, E. A., & Fonte, S. J. (2017). Land use as a driver of soil fertility and biodiversity across an agricultural landscape in the Central Peruvian Andes. *Ecological Applications*, *27*(4), 1138–1154. https://doi.org/10.1002/eap.1508

Deng, X., Li, Z., & Gibson, J. (2016). A review on trade-off analysis of ecosystem services for sustainable land-use management. In *Journal of Geographical Sciences* (Vol. 26, Issue 7, pp. 953–968). Science in China Press. https://doi.org/10.1007/s11442-016-1309-9

Depellegrin, D., Pereira, P., Misiunė, I., & Egarter-Vigl, L. (2016). Mapping ecosystem services potential in Lithuania. *International Journal of Sustainable Development and World Ecology*, *23*(5), 441–455. https://doi.org/10.1080/13504509.2016.1146176

der Biest Van, D'Hondt, R., Jacobs, S., Landuyt, D., Staes, J., Goethals, P., & Meire, P. (2014). EBI: An index for delivery of ecosystem service bundles. *Ecological Indicators*, *37*, *Part A*, 252–265. https://doi.org/10.1016/j.ecolind.2013.04.006

Dixon, John; Gulliver, Aidan; Gibbon, David; Hall, M. (2001). Farming Systems and Poverty Farming Systems and Poverty:Improving Farmers' Livelihoods in a Changing World. *FAO and World Bank, Rome and Washington DC*, 412. https://doi.org/10.1017/S0014479702211059

Dou, H., Li, X., Li, S., & Dang, D. (2018). How to Detect Scale Effect of Ecosystem Services Supply? A Comprehensive Insight from Xilinhot in Inner Mongolia, China. *Sustainability*, *10*(10), 3654. https://doi.org/10.3390/su10103654

Du, X., Jin, X., Yang, X., Yang, X., & Zhou, Y. (2014). Spatial pattern of land use change and its driving force in Jiangsu province. *International Journal of Environmental Research and Public Health*, *11*(3), 3215–3232. https://doi.org/10.3390/ijerph110303215

Duchicela, S. A., Cuesta, F., Pinto, E., Gosling, W. D., & Young, K. R. (2019). Indicators for assessing tropical alpine rehabilitation practices. *Ecosphere*, *10*(2), e02595. https://doi.org/10.1002/ecs2.2595

Egarter Vigl, L., Tasser, E., Schirpke, U., & Tappeiner, U. (2017). Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. *Regional Environmental Change*, *17*(8), 2237–2250. https://doi.org/10.1007/s10113-017-1132-6

Egoh, B. N., Reyers, B., Rouget, M., & Richardson, D. M. (2011). Identifying priority areas for ecosystem service management in South African grasslands. *Journal of Environmental Management*, *92*(6), 1642–1650. https://doi.org/10.1016/j.jenvman.2011.01.019

Eigenbrod, F., Bell, V. A., Davies, H. N., Heinemeyer, A., Armsworth, P. R., & Gaston, K. J. (2011). The impact of projected increases in urbanization on ecosystem services. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1722), 3201–3208. https://doi.org/10.1098/rspb.2010.2754

Ektvedt, T. M., Vetaas, O. R., & Lundberg, A. (2012). Land-cover changes during the past 50 years in the semi-arid tropical forest region of northern peru. *Erdkunde*, *66*(1), 57–75. https://doi.org/10.3112/erdkunde.2012.01.05

ESRI. (2014). ArcGIS Desktop: Release 10.3. In *Redlands CA* (p. Environmental Systems Research Institute.). https://doi.org/10.1209/epl/i2001-00551-4

European Environment Agency. (2013). *Common International Classification of Ecosystem Services (CICES)*. Cices. http://cices.eu/

Feixiang, S. U. N., Yihe, L. Y. U., Bojie, F. U., & Jian, H. U. (2016). Hydrological Services by Mountain Ecosystems in Qilian Mountain of China : A Review. *Chinese Geographical Science*, *26*(2), 174–187. https://doi.org/10.1007/s11769-015-0791-9

Felipe-Lucia, M. R., Comín, F. A., & Bennett, E. M. (2014). Interactions Among Ecosystem Services Across Land Uses in a Floodplain Agroecosystem. *Ecology and Society*, *19*(1), art20. https://doi.org/10.5751/ES-06249-190120

Fjeldså, J. (2002). Polylepis forests – vestiges of a vanishing ecosystem in the Andes. *Ecotropica*, *8*, 111–123.

Fonte, S. J., Vanek, S. J., Oyarzun, P., Parsa, S., Quintero, D. C., Rao, I. M., & Lavelle, P. (2012). Pathways to Agroecological Intensification of Soil Fertility Management by Smallholder Farmers in the Andean Highlands. In *Advances in Agronomy* (Vol. 116, pp. 125–184). https://doi.org/10.1016/B978-0-12-394277-7.00004-X

Frey, B. J., & Dueck, D. (2007). Clustering by passing messages between data points. *Science*, *315*(5814), 972–976. https://doi.org/10.1126/science.1136800

Geist, H. J., & Lambin, E. F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience*, *52*(2), 143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:pcaudf]2.0.co;2

Geological Mining and Metallurgical Institute. (2018). *Mapa catastro minero del Perú* (p. 1).

Gibbon, A., Silman, M. R., Malhi, Y., Fisher, J. B., Meir, P., Zimmermann, M., Dargie, G. C., Farfan, W. R., & Garcia, K. C. (2010). Ecosystem Carbon Storage Across the Grassland–Forest Transition in the High Andes of Manu National Park, Peru. *Ecosystems*, *13*(7), 1097–1111. https://doi.org/10.1007/s10021-010-9376-8

Gobierno Regional de Ayacucho. (2013). *Zonificación Ecológica Económica - Ayacucho*.

Gobierno Regional de Huancavelica. (2013). *MESO ZONIFICACION ECOLOGICA y ECONOMICA DEL DEPARTAMENTO DE HUANCAVELICA*.

Grêt-Regamey, A., Brunner, S. H., & Kienast, F. (2012). Mountain Ecosystem Services: Who Cares? *Mountain Research and Development*, *32*(S1), S23–S34. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1

Gutiérrez B., N., Gärtner, S., López H., J. Y., Pacheco, C. E., & Reif, A. (2013). The recovery of the lower montane cloud forest in the Mucujún watershed, Mérida, Venezuela. *Regional Environmental Change*, *13*(5), 1069–1085. https://doi.org/10.1007/s10113-013-0413-y

Haines-Young, R., & Potschin, M. (2018). CICES V5. 1. Guidance on the Application of the Revised Structure. *Fabis Consulting*, *January*, 53. www.cices.eu

Haller, A. (2012). Vivid valleys, pallid peaks? Hypsometric variations and rural-urban land change in the Central Peruvian Andes. *Applied Geography*, *35*(1–2), 439–447. https://doi.org/10.1016/j.apgeog.2012.09.009

Haller, A., & Borsdorf, A. (2013). Huancayo Metropolitano. *Cities*, *31*, 553–562. https://doi.org/10.1016/J.CITIES.2012.04.004

Hamann, M., Biggs, R., & Reyers, B. (2015). Mapping social-ecological systems: Identifying “green-loop” and “red-loop” dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change*, *34*, 218–226. https://doi.org/10.1016/j.gloenvcha.2015.07.008

Hartman, B. D., Bookhagen, B., & Chadwick, O. A. (2016). The effects of check dams and other erosion control structures on the restoration of Andean bofedal ecosystems. *Restoration Ecology*, *24*(6), 761–772. https://doi.org/10.1111/rec.12402

Hein, L., van Koppen, C. S. A. K., van Ierland, E. C., & Leidekker, J. (2016). Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. *Ecosystem Services*, *21*, 109–119. https://doi.org/10.1016/j.ecoser.2016.07.008

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. In *Environmental Research Letters* (Vol. 7, Issue 4, p. 044009). IOP Publishing. https://doi.org/10.1088/1748-9326/7/4/044009

Hou, Y., Burkhard, B., & Müller, F. (2013). Uncertainties in landscape analysis and ecosystem service assessment. *Journal of Environmental Management*, *127*, S117–S131. https://doi.org/10.1016/j.jenvman.2012.12.002

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*(1), 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

INEI - National Institute of Statistics and Informatics. (n.d.-a). *III Censo Nacional Agropecuario 1994 (III CENAGRO)*. http://censos.inei.gob.pe/bcoCuadros/IIIcenagro.htm

INEI - National Institute of Statistics and Informatics. (n.d.-b). *National census*. https://www.inei.gob.pe/estadisticas/censos/

INEI - National Institute of Statistics and Informatics. (2014). *Encuesta Nacional de Hogares*. https://webinei.inei.gob.pe/anda_inei/index.php/catalog/ENC_HOGARES

Jacobs, S., Burkhard, B., Van Daele, T., Staes, J., & Schneiders, A. (2015). ‘The Matrix Reloaded’: A review of expert knowledge use for mapping ecosystem services. *Ecological Modelling*, *295*, 21–30. https://doi.org/10.1016/j.ecolmodel.2014.08.024

Jameson, J. S., & Ramsay, P. M. (2007). Changes in high-altitude Polylepis forest cover and quality in the Cordillera de Vilcanota, Perú, 1956–2005. *Biological Conservation*, *138*(1–2), 38–46. https://doi.org/10.1016/J.BIOCON.2007.04.008

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., Chacón-Moreno, E., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009). *Ecosistemas de los Andes del Norte y Centro*. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. http://www.saber.ula.ve/handle/123456789/39336

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009a). *Ecosistemas de los Andes del Norte y*

Centro. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. https://doi.org/10.1164/rccm.200702-271OC

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009b). *Mapa de ecosistemas de los andes del norte y centro. Bolivia,Colombia, Ecuador, Perú y Venezuela*. www.infoandina.org/ecosistemasandinos

Knoke, T., Bendix, J., Pohle, P., Hamer, U., Hildebrandt, P., Roos, K., Gerique, A., Sandoval, M. L., Breuer, L., Tischer, A., Silva, B., Calvas, B., Aguirre, N., Castro, L. M., Windhorst, D., Weber, M., Stimm, B., Günter, S., Palomeque, X., … Beck, E. (2014). Afforestation or intense pasturing improve the ecological and economic value of abandoned tropical farmlands. *Nature Communications*, *5*. https://doi.org/10.1038/ncomms6612

Koschke, L., Fürst, C., Frank, S., & Makeschin, F. (2012). A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecological Indicators*, *21*, 54–66. https://doi.org/10.1016/j.ecolind.2011.12.010

Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M. R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P. J., Verburg, P. H., & Reenberg, A. (2016). Hotspots of land use change in Europe. *Environmental Research Letters*, *11*(6), 064020. https://doi.org/10.1088/1748-9326/11/6/064020

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, *28*(1), 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. *Biometrics*, *33*(1), 159. https://doi.org/10.2307/2529310

Lautenbach, S., Kugel, C., Lausch, A., & Seppelt, R. (2011). Analysis of historic changes in regional ecosystem service provisioning using land use data. *Ecological Indicators*, *11*(2), 676–687. https://doi.org/10.1016/j.ecolind.2010.09.007

Lavorel, S., Bayer, A., Bondeau, A., Lautenbach, S., Ruiz-Frau, A., Schulp, N., Seppelt, R., Verburg, P., Teeffelen, A. van, Vannier, C., Arneth, A., Cramer, W., & Marba, N. (2017). Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. In *Ecological Indicators* (Vol. 74, pp. 241–260). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2016.11.015

Lee, E., Livino, A., Han, S. C., Zhang, K., Briscoe, J., Kelman, J., & Moorcroft, P. (2018). Land cover change explains the increasing discharge of the Paraná River. *Regional Environmental Change*, *18*(6), 1871–1881. https://doi.org/10.1007/s10113-018-1321-y

Lee, H., & Lautenbach, S. (2016). A quantitative review of relationships between ecosystem services. *Ecological Indicators*, *66*, 340–351. https://doi.org/10.1016/j.ecolind.2016.02.004

Legendre, P. (2018). Numerical ecology. In *Encyclopedia of Ecology* (pp. 487–493). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10595-0

Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M. R., Metzger, M. J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P. H., Verkerk, P. J., & Kuemmerle, T. (2018). Archetypical patterns and trajectories of land systems in Europe. *Regional*

Environmental Change, *18*(3), 715–732. https://doi.org/10.1007/s10113-015-0907-x

Li, T., Lü, Y., Fu, B., Hu, W., & Comber, A. J. (2019). Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: enhanced services while depressed synergies. *Ecological Indicators*, *99*, 332–342. https://doi.org/10.1016/j.ecolind.2018.12.041

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., & Li, S. (2015). Systems integration for global sustainability. In *Science* (Vol. 347, Issue 6225). https://doi.org/10.1126/science.1258832

Locatelli, B., Lavorel, S., Sloan, S., Tappeiner, U., & Geneletti, D. (2017). Characteristic trajectories of ecosystem services in mountains. In *Frontiers in Ecology and the Environment* (Vol. 15, Issue 3, pp. 150–159). Wiley-Blackwell. https://doi.org/10.1002/fee.1470

López-Moreno, J. I., Fontaneda, S., Bazo, J., Revuelto, J., Azorin-Molina, C., Valero-Garcés, B., Morán-Tejeda, E., Vicente-Serrano, S. M., Zubieta, R., & Alejo-Cochachín, J. (2014). Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. *Global and Planetary Change*, *112*, 1–11. https://doi.org/10.1016/j.gloplacha.2013.10.010

Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*(12), 2365–2407. https://doi.org/10.1080/0143116031000139863

MA. (2005). *Ecosystems and human well-being: synthesis report*. www.islandpress.org

Madrigal-Martínez, S., & Miralles i García, J. L. (2019a). Understanding land use changes in the central high-Andean moist Puna. *WIT Transactions on Ecology and the Environment*, *238*.

Madrigal-Martínez, S., & Miralles i García, J. L. (2019b). Land-change dynamics and ecosystem service trends across the central high-Andean Puna. *Scientific Reports*, *9*(1), 9688. https://doi.org/10.1038/s41598-019-46205-9

Maldonado Fonkén, M. S. (2014). An introduction to the bofedales of the Peruvian High Andes. *Mires and Peat*, *15*(15), 1–13. http://www.mires-and-peat.net/,ISSN1819-754X

Mark, B. G., & Seltzer, G. O. (2003). Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *Journal of Glaciology*, *49*(165), 271–281. https://doi.org/10.3189/172756503781830746

Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Del Amo, D. G., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I., Willaarts, B., González, J. A., Santos-Martín, F., Onaindia, M., López-Santiago, C., & Montes, C. (2012). Uncovering ecosystem service bundles through social preferences. *PLoS ONE*, *7*(6), e38970. https://doi.org/10.1371/journal.pone.0038970

Meacham, M., Queiroz, C., Norström, A. V., & Peterson, G. D. (2016). Social-ecological drivers of multiple ecosystem services: What variables explain patterns of ecosystem services across the Norrström drainage basin? *Ecology and Society*, *21*(1). https://doi.org/10.5751/ES-08077-210114

Metzger, M. J., Rounsevell, M. D. A., van den Heiligenberg, H. A. R. M., Pérez-Soba, M., & Hardiman, P. S. (2010). How personal judgment influences scenario development: An example for future rural development in Europe. *Ecology and*

Society, *15*(2), 27. https://doi.org/10.5751/ES-03305-150205
Ministry of Economy and Treasury. (n.d.). *Banco de Inversiones - invierte.pe*.
Ministry of Environment. (n.d.-a). *Geoservidor*. ZONIFICACIÓN ECOLÓGICA Y ECONÓMICA – ZEE. https://geoservidor.minam.gob.pe/zee-aprobadas/zee-aprobadas/
Ministry of Environment. (n.d.-b). *Mecanismos de retibucion por servicios ecosistemicos*. Retrieved October 4, 2019, from http://serviciosecosistemicos.minam.gob.pe/
Ministry of Environment. (2012). *Memoria descriptiva del mapa de cobertura vegetal del Peru*.
Ministry of Environment. (2014). *LA ESTRATEGIA NACIONAL DE DIVERSIDAD BIOLÓGICA AL 2021 Y SU PLAN DE ACCIÓN 2014-2018*.
Ministry of Environment. (2015a). *Mapa nacional de cobertura vegetal. Memoria descriptiva.* http://www.minam.gob.pe/patrimonio-natural/wp-content/uploads/sites/6/2013/10/MAPA-NACIONAL-DE-COBERTURA-VEGETAL-FINAL.compressed.pdf
Ministry of Environment. (2015b). *Mapa nacional de cobertura vegetal* (p. 1). Dirección General de Evaluación, Valoración y Financiamiento del Patrimonio Natural.
Ministry of Environment. (2017). *ESTADO SITUACIONAL DE LA ZONIFICACIÓN ECOLÓGICA Y ECONÓMICA (ZEE) A NIVEL REGIONAL.*
Ministry of Environment. (2018). *Mapa nacional de ecosistemas del Perú. Memoria Descriptiva*.
Ministry of Environment, & SERNANP. (2016). *ÁREAS NATURALES PROTEGIDAS DEL PERÚ Conservación para el desarrollo sostenible*.
Miranda, A., Altamirano, A., Cayuela, L., Pincheira, F., & Lara, A. (2015). Different times, same story: Native forest loss and landscape homogenization in three physiographical areas of south-central of Chile. *Applied Geography*, *60*, 20–28. https://doi.org/10.1016/j.apgeog.2015.02.016
Molina, A., Vanacker, V., Brisson, E., Mora, D., & Balthazar, V. (2015). Multidecadal change in streamflow associated with anthropogenic disturbances in the tropical Andes. *Hydrology and Earth System Sciences*, *19*(10), 4201–4213. https://doi.org/10.5194/hess-19-4201-2015
Montoya-Tangarife, C., de la Barrera, F., Salazar, A., & Inostroza, L. (2017). Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaíso, Chile. *PLOS ONE*, *12*(11), e0188117. https://doi.org/10.1371/journal.pone.0188117
Mouchet, M. A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., & Lavorel, S. (2014). An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Global Environmental Change*, *28*(1), 298–308. https://doi.org/10.1016/j.gloenvcha.2014.07.012
Mulvaney, D., Robbins, P., & Freeman, C. P. (2012). Vegan. In *Green Food: An A-to-Z Guide* (p. 2). https://doi.org/10.4135/9781412971874.n145
Nakayama, T., Watanabe, M., Tanji, K., & Morioka, T. (2007). Effect of underground urban structures on eutrophic coastal environment. *Science of the Total Environment*, *373*(1), 270–288. https://doi.org/10.1016/j.scitotenv.2006.11.033
National Institute of Natural Resources. (2000). *Mapa forestal del Perú* (p. 1). INRENA.
Naturserve. (2009). *International Ecological Classification Standard: Terrestrial*

Ecological Classifications. Sistemas Ecológicos de los Andes del Norte y Centro.
Nelson, G. C., Bennett, E., Berhe, A. A., Cassman, K., DeFries, R., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., Levy, M., Marco, D., Nakicenovic, N., O'Neill, B., Norgaard, R., Petschel-Held, G., Ojima, D., Pingali, P., Watson, R., & Zurek, M. (2006). Anthropogenic drivers of ecosystem change: An overview. In *Ecology and Society* (Vol. 11, Issue 2, p. 29). https://doi.org/10.5751/ES-01826-110229
Oliveras, I., Girardin, C., Doughty, C. E., Cahuana, N., Arenas, C. E., Oliver, V., Huaraca Huasco, W., & Malhi, Y. (2014). Andean grasslands are as productive as tropical cloud forests. *Environmental Research Letters*, *9*(11), 115011. https://doi.org/10.1088/1748-9326/9/11/115011
Oscanoa, L., & Flores, E. (2016). INFLUENCIA DE TÉCNICAS DE MEJORA DE SUELOS SOBRE LA FUNCIÓN HÍDRICA DE PASTOS NATURALES ALTOANDINOS. *Ecología Aplicada*, *15*(2), 91. https://doi.org/10.21704/rea.v15i2.748
Pan, Y., Wu, J., & Xu, Z. (2014). Analysis of the tradeoffs between provisioning and regulating services from the perspective of varied share of net primary production in an alpine grassland ecosystem. *Ecological Complexity*, *17*(1), 79–86. https://doi.org/10.1016/j.ecocom.2013.11.001
Patton, M. (2002). *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*.
Pestalozzi, H. (2000). Sectoral Fallow Systems and the Management of Soil Fertility: The Rationality of Indigenous Knowledge in the High Andes of Bolivia. *Mountain Research and Development*, *20*(1), 64–71. https://doi.org/http://dx.doi.org/10.1659/0276-4741(2000)020[0064:SFSATM]2.0.CO;2
Petz, K., Alkemade, R., Bakkenes, M., Schulp, C. J. E., van der Velde, M., & Leemans, R. (2014). Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Global Environmental Change*, *29*, 223–234. https://doi.org/10.1016/j.gloenvcha.2014.08.007
Postigo, J. C. (2014). Perception and Resilience of Andean Populations Facing Climate Change. *Journal of Ethnobiology*, *34*(3), 383–400. https://doi.org/10.2993/0278-0771-34.3.383
Qiao, X., Gu, Y., Zou, C., Xu, D., Wang, L., Ye, X., Yang, Y., & Huang, X. (2019). Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. *Science of the Total Environment*, *651*, 218–229. https://doi.org/10.1016/j.scitotenv.2018.09.135
Queiroz, C., Meacham, M., Richter, K., Norström, A. V., Andersson, E., Norberg, J., & Peterson, G. (2015). Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. *Ambio*, *44*(1), 89–101. https://doi.org/10.1007/s13280-014-0601-0
Quintero-Gallego, M. E., Quintero-Angel, M., & Vila-Ortega, J. J. (2018). Exploring land use/land cover change and drivers in Andean mountains in Colombia: A case in rural Quindío. *Science of the Total Environment*, *634*, 1288–1299. https://doi.org/10.1016/j.scitotenv.2018.03.359
R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. In *R Foundation for Statistical Computing* (Vol. 1, Issue 2.11.1, p. 409). https://doi.org/10.1007/978-3-540-74686-7

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J. E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., … Wagnon, P. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere*, *7*(1), 81–102. https://doi.org/10.5194/tc-7-81-2013

Raudsepp-Hearne, C, Peterson, G. D., & Bennett, E. M. (2010). Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences*, *107*(11), 5242–5247. https://doi.org/10.1073/pnas.0907284107

Raudsepp-Hearne, Ciara, & Peterson, G. D. (2016). Scale and ecosystem services: How do observation, management, and analysis shift with scale—lessons from Québec. *Ecology and Society*, *21*(3), art16. https://doi.org/10.5751/ES-08605-210316

Renard, D., Rhemtulla, J. M., & Bennett, E. M. (2015). Historical dynamics in ecosystem service bundles. *Proceedings of the National Academy of Sciences*, *112*(43), 13411–13416. https://doi.org/10.1073/pnas.1502565112

Restrepo, J. D., Kettner, A. J., & Syvitski, J. P. M. (2015). Recent deforestation causes rapid increase in river sediment load in the Colombian Andes. *Anthropocene*, *10*, 13–28. https://doi.org/10.1016/j.ancene.2015.09.001

Rieb, J. T., Chaplin-Kramer, R., Daily, G. C., Armsworth, P. R., Böhning-Gaese, K., Bonn, A., Cumming, G. S., Eigenbrod, F., Grimm, V., Jackson, B. M., Marques, A., Pattanayak, S. K., Pereira, H. M., Peterson, G. D., Ricketts, T. H., Robinson, B. E., Schröter, M., Schulte, L. A., Seppelt, R., … Bennett, E. M. (2017). When, Where, and How Nature Matters for Ecosystem Services: Challenges for the Next Generation of Ecosystem Service Models. *BioScience*, *67*(9), 820–833. https://doi.org/10.1093/biosci/bix075

Roces-Díaz, J. V., Vayreda, J., Banqué-Casanovas, M., Díaz-Varela, E., Bonet, J. A., Brotons, L., De-Miguel, S., Herrando, S., & Martínez-Vilalta, J. (2018). The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships. *Science of the Total Environment*, *626*, 1270–1283. https://doi.org/10.1016/j.scitotenv.2018.01.150

Rodríguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., Dobson, A. P., & Peterson, G. D. (2006). Trade-offs across Space , Time , and Ecosystem Services. *Ecology and Society*, *11*(1). https://cals.arizona.edu/classes/ram696a/ES tradeoffs 2006.pdf

Rodríguez, L. C., Pascual, U., & Niemeyer, H. M. (2006). Local identification and valuation of ecosystem goods and services from Opuntia scrublands of Ayacucho, Peru. *Ecological Economics*, *57*(1), 30–44. https://doi.org/10.1016/J.ECOLECON.2005.03.022

Rolando, J. L., Dubeux, J. C., Perez, W., Ramirez, D. A., Turin, C., Ruiz-Moreno, M., Comerford, N. B., Mares, V., Garcia, S., & Quiroz, R. (2017). Soil organic carbon stocks and fractionation under different land uses in the Peruvian high-Andean Puna. *Geoderma*, *307*, 65–72. https://doi.org/10.1016/j.geoderma.2017.07.037

Rolando, J. L., Turin, C., Ramírez, D. A., Mares, V., Monerris, J., & Quiroz, R. (2017). Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes. In *Agriculture, Ecosystems and Environment* (Vol. 236, pp. 221–233). Elsevier.

https://doi.org/10.1016/j.agee.2016.12.010
Rounsevell, M. D. A., Pedroli, B., Erb, K. H., Gramberger, M., Busck, A. G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M. J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P. H., & Wolfslehner, B. (2012). Challenges for land system science. *Land Use Policy*, *29*(4), 899–910. https://doi.org/10.1016/j.landusepol.2012.01.007
Rubiano, K., Clerici, N., Norden, N., & Etter, A. (2017). Secondary forest and shrubland dynamics in a highly transformed landscape in the Northern Andes of Colombia (1985-2015). *Forests*, *8*(6). https://doi.org/10.3390/f8060216
Saavedra Briones, P., & Sepúlveda-Varas, A. (2016). SYSTEMATIC TRANSITIONS IN LAND USE AND LAND COVER IN A PRE-ANDEAN SUB-WATERSHED WITH HIGH HUMAN INTERVENTION IN THE ARAUCANIA REGION, CHILE. *Ciencia e Investigación Agraria*, *43*(3), 6–6. https://doi.org/10.4067/s0718-16202016000300006
Saidi, N., & Spray, C. (2018). Ecosystem services bundles: Challenges and opportunities for implementation and further research. In *Environmental Research Letters* (Vol. 13, Issue 11, p. 113001). IOP Publishing. https://doi.org/10.1088/1748-9326/aae5e0
Salvador, F., Monerris, J., & Rochefort, L. (2014). Peatlands of the Peruvian Puna ecoregion: types, characteristics and disturbance. *Mires and Peat*, *15*(3), 1–17. http://www.mires-and-peat.net/,
Scholes, R. J., Reyers, B., Biggs, R., Spierenburg, M. J., & Duriappah, A. (2013). Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issue 1, pp. 16–25). Elsevier. https://doi.org/10.1016/j.cosust.2013.01.004
Scolozzi, R., Morri, E., & Santolini, R. (2012). Delphi-based change assessment in ecosystem service values to support strategic spatial planning in Italian landscapes. *Ecological Indicators*, *21*, 134–144. https://doi.org/10.1016/j.ecolind.2011.07.019
Segnini, A., Posadas, A., Quiroz, R., Milori, D. M. B. P., Saab, S. C., Neto, L. M., & Vaz, C. M. P. (2010). Spectroscopic Assessment of Soil Organic Matter in Wetlands from the High Andes. *Soil Science Society of America Journal*, *74*(6), 2246. https://doi.org/10.2136/sssaj2009.0445
SERFOR. (n.d.). *Plataforma de seguimiento de la Zonificación Forestal (v1.1)*. Retrieved September 6, 2019, from https://datastudio.google.com/u/0/reporting/1rBWIgdSv6bguI4RaAyMnpnW9myR3t-sB/page/qCMh
SERNANP. (2019). *ÁREAS NATURALES PROTEGIDAS DE ADMINISTRACIÓN NACIONAL CON CATEGORIA DEFINITIVA*.
Skarbø, K., & VanderMolen, K. (2016). Maize migration: key crop expands to higher altitudes under climate change in the Andes. *Climate and Development*, *8*(3), 245–255. https://doi.org/10.1080/17565529.2015.1034234
Sohel, M. S. I., Ahmed Mukul, S., & Burkhard, B. (2015). Landscape's capacities to supply ecosystem services in Bangladesh: A mapping assessment for Lawachara National Park. *Ecosystem Services*, *12*, 128–135. https://doi.org/10.1016/j.ecoser.2014.11.015
Spake, R., Lasseur, R., Crouzat, E., Bullock, J. M., Lavorel, S., Parks, K. E., Schaafsma, M.,

Bennett, E. M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G. D., Schulp, C. J. E., Thuiller, W., Turner, M. G., Verburg, P. H., & Eigenbrod, F. (2017). Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. *Global Environmental Change*, *47*, 37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004

Stepputat, F., & Nyberg Sørensen, N. (2001). The rise and fall of "Internally Displaced People" in the Central Peruvian Andes. *Development and Change*, *32*(4), 769–791. https://doi.org/10.1111/1467-7660.00225

Stürck, J., & Verburg, P. H. (2017). Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. *Landscape Ecology*, *32*(3), 481–500. https://doi.org/10.1007/s10980-016-0459-6

Swinton, S. M., & Quiroz, R. (2003). Poverty and the deterioration of natural soil capital in the Peruvian altiplano. *Environment, Development and Sustainability*, *5*(3–4), 477–490. https://doi.org/10.1023/A:1025785231559

Tito, R., Vasconcelos, H. L., & Feeley, K. J. (2018). Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. *Global Change Biology*, *24*(2), e592–e602. https://doi.org/10.1111/gcb.13959

Tomscha, S. A., & Gergel, S. E. (2016). Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecology and Society*, *21*(1), art43. https://doi.org/10.5751/ES-08345-210143

Tovar, C., Seijmonsbergen, A. C., & Duivenvoorden, J. F. (2013). Monitoring land use and land cover change in mountain regions: An example in the Jalca grasslands of the Peruvian Andes. *Landscape and Urban Planning*, *112*(1), 40–49. https://doi.org/10.1016/j.landurbplan.2012.12.003

Trabucchi, M., Comín, F. A., & O'Farrell, P. J. (2013). Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services. *Regional Environmental Change*, *13*(4), 911–926. https://doi.org/10.1007/s10113-012-0392-4

Turner, B. L. (2002). Toward Integrated Land-Change Science: Advances in 1.5 Decades of Sustained International Research on Land-Use and Land-Cover Change. In B. C. Steffen W., Jäger J., Carson D.J. (Ed.), *Challenges of a Changing Earth. Global Change — The IGBP Series* (pp. 21–26). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-19016-2_3

Turner, K. G., Odgaard, M. V., Bøcher, P. K., Dalgaard, T., & Svenning, J. C. (2014). Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landscape and Urban Planning*, *125*, 89–104. https://doi.org/10.1016/j.landurbplan.2014.02.007

Turner, M. G., O'Neill, R. V., Gardner, R. H., & Milne, B. T. (1989). Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecology*, *3*(3–4), 153–162. https://doi.org/10.1007/BF00131534

Vallet, A., Locatelli, B., Levrel, H., Wunder, S., Seppelt, R., Scholes, R. J., & Oszwald, J. (2018). Relationships Between Ecosystem Services: Comparing Methods for Assessing Tradeoffs and Synergies. *Ecological Economics*, *150*, 96–106. https://doi.org/10.1016/j.ecolecon.2018.04.002

Van Jaarsveld, A. S., Biggs, R., Scholes, R. J., Bohensky, E., Reyers, B., Lynam, T., Musvoto, C., & Fabricius, C. (2005). Measuring conditions and trends in ecosystem

services at multiple scales: The Southern African Millennium Ecosystem Assessment (SAfMA) experience. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 425–441. https://doi.org/10.1098/rstb.2004.1594

Vásquez, E., Ladd, B., & Borchard, N. (2014). Carbon storage in a high-altitude Polylepis woodland in the Peruvian Andes. *Alpine Botany*, *124*(1), 71–75. https://doi.org/10.1007/s00035-014-0126-y

Verhagen, W., Van Teeffelen, A. J. A., Baggio Compagnucci, A., Poggio, L., Gimona, A., & Verburg, P. H. (2016). Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. *Landscape Ecology*, *31*(7), 1457–1479. https://doi.org/10.1007/s10980-016-0345-2

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., & Bradley, R. S. (2008). Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, *89*(3–4), 79–96. https://doi.org/10.1016/J.EARSCIREV.2008.04.002

Wei, H., Fan, W., Lu, N., Xu, Z., Liu, H., Chen, W., Ulgiati, S., Wang, X., & Dong, X. (2019). Integrating biophysical and sociocultural methods for identifying the relationships between ecosystem services and land use change: Insights from an Oasis area. *Sustainability (Switzerland)*, *11*(9). https://doi.org/10.3390/su11092598

Wiegers, E. S., Hijmans, R. J., Herve, D., & Fresco, L. O. (1999). Land use intensification and disintensification in the Upper Canete valley, Peru. *Human Ecology*, *27*(2), 319–339. https://doi.org/10.1023/a:1018729428781

Wulder, M. A., Coops, N. C., Roy, D. P., White, J. C., & Hermosilla, T. (2018). Land cover 2.0. In *International Journal of Remote Sensing* (Vol. 39, Issue 12, pp. 4254–4284). https://doi.org/10.1080/01431161.2018.1452075

Xu, S., Liu, Y., Wang, X., & Zhang, G. (2017). Scale effect on spatial patterns of ecosystem services and associations among them in semi-arid area: A case study in Ningxia Hui Autonomous Region, China. *Science of the Total Environment*, *598*, 297–306. https://doi.org/10.1016/j.scitotenv.2017.04.009

Yang, G., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C., Du, Y., Fan, X., Ren, Y., & Chang, J. (2015). Using ecosystem service bundles to detect trade-offs and synergies across urban-rural complexes. *Landscape and Urban Planning*, *136*, 110–121. https://doi.org/10.1016/j.landurbplan.2014.12.006

Young, B. E., Young, K. R., & Josse, C. (2008). Vulnerability of Tropical Andean Ecosystems to Climate Change. *Climate Change and Biodiversity in the Tropical Andes*, 170–181.

Young, K. R. (2009). Andean land use and biodiversity: Humanized landscapes in a time of change. *Annals of the Missouri Botanical Garden*, *96*(3), 492–507. https://doi.org/10.3417/2008035

Young, K. R. (2014). Ecology of land cover change in glaciated tropical mountains. *Revista Peruana de Biologia*, *21*(3), 259–270. https://doi.org/10.15381/rpb.v21i3.10900

Zen, M., Candiago, S., Schirpke, U., Egarter Vigl, L., & Giupponi, C. (2019). Upscaling ecosystem service maps to administrative levels: beyond scale mismatches. *Science of the Total Environment*, *660*, 1565–1575. https://doi.org/10.1016/j.scitotenv.2019.01.087

Zheng, Z., Fu, B., Hu, H., & Sun, G. (2014). A method to identify the variable ecosystem services relationship across time: a case study on Yanhe Basin, China. *Landscape Ecology*, *29*(10), 1689–1696. https://doi.org/10.1007/s10980-014-0088-x

Zimmermann, M., Meir, P., Silman, M. R., Fedders, A., Gibbon, A., Malhi, Y., Urrego, D. H., Bush, M. B., Feeley, K. J., Garcia, K. C., Dargie, G. C., Farfan, W. R., Goetz, B. P., Johnson, W. T., Kline, K. M., Modi, A. T., Rurau, N. M. Q., Staudt, B. T., & Zamora, F. (2010). No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes. *Ecosystems*, *13*(1), 62–74. https://doi.org/10.1007/s10021-009-9300-2

ARTICLE

LAND-CHANGE DYNAMICS AND ECOSYSTEM SERVICE TRENDS ACROSS THE CENTRAL HIGH-ANDEAN PUNA

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Mountain landscapes provide multiple ecosystem services that are continually vulnerable to land-change. These complex variations over space and time need to be clustered and explained to develop efficient and sustainable land management processes. We completed a spatiotemporal analysis that describes how different patterns of 6 land-change dynamics impact on the supply of 7 ecosystem services over a period of 14 years and across 25 provinces in the central high-Andean Puna of Peru. The appraisal describes: (1) how clusters of land-change dynamics are linked to ecosystem service bundles; (2) which are the dominant land-change dynamics that influence changes in ecosystem service bundles and (3) how multiple ecosystem service provision and relationships vary over space and time. Our analysis addressed agricultural de-intensification, agricultural expansion, natural processes, urbanization and deforestation as the most critical land-change dynamics across the central high-Andean region over time. Our results show that most of the provinces were mainly described by a small set of land-change dynamics that configured four types of ecosystem service bundles. Moreover, our study demonstrated that different patterns of land-change dynamics can have the same influence on the ecosystem service bundle development, and transformation of large areas are not necessarily equivalent to high variations in ecosystem service supply. Overall, this study provides an approach to facilitate the incorporation of ES at multiple scales allowing an easy interpretation of the region development that can contribute to land management actions and policy decisions.

Introduction

Half of the world population depends on mountain ecosystem resources that are continually vulnerable to land-change(MA, 2005), mainly determined by the consequences of human activities(Lambin et al., 2003) and by natural processes. Deforestation, agricultural intensification, agricultural de-intensification and urbanization are complex land-change dynamics documented in the high-Andean region(Aide et al., 2013; Aide & Grau, 2004; Wiegers et al., 1999; K. R. Young, 2014), yet, in-depth multi-temporal change approaches are required(Boillat et al., 2017). Understanding this complexity can help to implement land management processes to balance biodiversity conservation with human needs(Rounsevell et al., 2012) and also to measure the changes produced in the supply of ecosystem services(Levers et al., 2018; Locatelli et al., 2017).

Ecosystem service (hereafter ES) concept, the human well-being obtained from nature(MA, 2005), has become an important integrated framework in sustainability science(Liu et al., 2015). The ES framework facilitates ecosystem conservation opportunities(Abson et al., 2014) and affords innovative and valuable data to help decision-making(Albert et al., 2014). In this context, land use/land cover (hereafter LULC) models provide a high performance for explaining the provision of individual ES(Burkhard et al., 2009), even so limitations are found predicting cultural and some regulating services(Meacham et al., 2016). Evaluation of ES using LULC maps and expert estimation is worldwide extended(Jacobs et al., 2015), but scarce samples are found in mountain regions (e.g.(Balthazar et al., 2015; Bhandari et al., 2016)) and none in the phytoregion of moist Puna. This technique, ES matrix model(Burkhard et al., 2009), could overcome the lack of data present in the region(Boillat et al., 2017) and to solve the necessity of more ES appraisals in highland territories(Grêt-Regamey et al., 2012).

However, mountain landscapes provide multiple ES that varies over space and time manifested by several land-changes dynamics, making necessary a spatiotemporal analysis to advance the knowledge of ES trajectories(Egarter Vigl et al., 2017; Lautenbach et al., 2011; Renard et al., 2015), likewise the positive or negative interactions between them, namely synergies or trade-offs respectively(J. P. Rodríguez et al., 2006). This complex ecological state, of multiple ES linked to land use in change tendencies, is clarified with ES bundles(der Biest Van et al., 2014). Bundles of ES, sets of ES co-occurring with human activities across a landscape over time(C Raudsepp-Hearne et al., 2010), contribute to incorporate ES models into land use planning(Crouzat et al., 2015; der Biest Van et al., 2014). Nevertheless, predictive variables need to be assessed to complete ES bundles performance(Meacham et al., 2016; Spake et al., 2017). At present, there are no studies of ES bundles in the high-Andean region(Spake et al., 2017) linking clusters of land-change dynamics with bundles of ES trends to be used as a framework for improving stakeholder decisions in land planning.

Therefore, we develop a spatiotemporal analysis that describes how different patterns of 6 land-change dynamics impact on the supply of 7 ecosystem services over time (from 2000 to 2013) and across 25 provinces in the central high-Andean Puna of Peru (Fig 1 left). We select this section of the moist Puna region (64,025 km^2) as our study area because of its ecological significance and data availability. Moist Puna has an ecological importance as a sequester of great amounts of soil organic carbon, regulation of water flow and provision of farming outputs(Rolando, Turin, et al., 2017). The 6 land-change dynamics represent the transitions assessed (Table S1) between the eleven relevant LULC units (Fig 1 right) in the study period. The 7 selected ES include site-specific services from two main categories (five regulating and two provisioning) identified by the Common International Classification of Ecosystem Services(European Environment Agency, 2013) and Burkhard et al.(Burkhard et al., 2014): two regulating services related to mediation of flows (regulation of soil erosion and water flow regulation); one ES related to filtration, sequestration, storage or accumulation by ecosystems (water purification); two services linked to the maintenance of physical, chemical, biological conditions (soil quality and global climate regulation) and, finally, two provisioning services related to nutrition (crops and reared animals). First, we consult 63 practitioners in order to estimate the maximum capacity of each LULC unit to supply each of the regulating ES and we complete the potential supply of provisioning services from official model results. Second, we incorporate time in the spatial analysis to assess the land-change dynamics as achieved by other studies (e.g.(Egarter Vigl et al., 2017; Lautenbach et al., 2011)). Third, we investigate the associations between clusters of land-change dynamics and ES bundles, to identify positive, negative or contrasting patterns. Fourth, we determine the explanatory variables (e.g.(Renard et al., 2015)) that best predict these associations.

Our work provides a comprehensive view of how clusters of land-change dynamics are linked to ES bundles, and the social-ecological determinants (firewood, rural population and mining) that explain these associations. We hypothesize that higher rates of LULC changes hardly modify ES supply and

configuration of these changes had a critical role in ES bundle development; but our findings show that transformation of large landscapes are not necessarily equivalent to high variations in ES, whereas small land alterations are corresponding to slight impacts in ES. Our study highlights agricultural de-intensification, agricultural expansion and natural processes as the most significant land-change dynamics that influence changes in ES bundles. We confirm that multiple ES provision and relationships vary over space and time. We hope our study will provide information that might promote and facilitate the incorporation of ES at multiple scales for sustainable land management.

Results

Ecosystem service matrix scores and sensitivity analysis

The expert scores for regulating ES and the results of the standardised method for provisioning ES are presented in Fig 2A. The details of the quantity of consulting experts, the outliers identified and the contributing answers for each LULC/regulating ES pairs are systematized in Online Resource 1.

Peatbogs and high-Andean wetlands (2.46% of the study area in 2013) afforded the highest potential for both ES sections. Low forest, natural grasslands and shrublands gave higher values for regulating ES. These classes covered separately 0.58%, 61.39% and 20.05% of the territory in 2013. Glaciers and water bodies had very high potential regulating water flow. Water bodies and water courses got high performance purifying water, whereas forest plantations highlighted by its soil erosion control and carbon sequestration. Agricultural areas (10.10% of the study area in 2013) presented low and medium potential for crops and livestock services, respectively. Finally, continuous urban fabric and sparsely vegetated areas are related with no relevance supply in almost all the ES.

The sensitivity analysis was carried out to evaluate the variability and the uncertainty in the regulating ES matrix scores. The variability of the expert responses had a low significance, varying between SD=0 for agreements and up to SD=1.918 for the biggest discrepancies (Fig 2B). The results showed that 5% of the scores got an unanimous response, while 55% had very low variability. Glaciers and water bodies gathered the higher SD values with global climate change and regulation of soil erosion services, respectively. Although, water purification was the service that accumulated more percentage of discrepancies (11%), showing low reliability. Whereas, water flow regulation and soil quality services grouped 15% of low variability responses.

The comparison between the sensitivity matrices 1 and 2 (Fig 2C) and the regulating ES matrix indicated 87% and 84% of overall agreement of cells under equal class of the potential supply, respectively. The minor differences supposed an increment or decrement one level in the potential supply scale in 7 and 9 expert scores after adding or deducting the SE value as it should. Kappa coefficient for the sensitivity matrices 1 and 2 were 0.84 and 0.79 representing “almost perfect” and “substantial” accuracy. By LULC, continuous urban fabric and forest plantation continued undisturbed after submitting the changes. Sparsely vegetated areas and water bodies have the largest potential increment, while agricultural areas and water courses show the biggest supplying reduction. By regulating ES, water flow regulation and soil quality services were the most upgraded, quite the opposite occurred with water purification and global climate regulation services. In summary, the low variability of the responses and stability around the mean values signified robustness of the regulating ES matrix scores for the studied area.

Quantification of individual LULC changes and clusters of land-change dynamics

The details of LULC changes between 2000 and 2013 are presented in Table S1 (Online Resources 1). In terms of the absolute area, 8192.8 km^2 (12.7%) were transformed. Kappa analyses confirmed a “substantial” consistency among the two LULC maps, with an overall agreement that reached the 87.2%. Natural grasslands coincided to be the largest class in both years (above 60%) seconded for shrublands and agricultural areas, configuring the 90% of the study landscape. However, thirty-one types of transitions were assessed and grouped in six land-change dynamics (Table 1). Agricultural expansion (D1) was the more extensive dynamic of LULC change, implicating the conversion of low forest, shrublands and natural grasslands. Agricultural de-intensification (D2) represented an increase of grasslands and shrublands due to fallowing and/or land abandonment. Deforestation (D3) of low forest (12.5%) gave way to shrublands. Dynamic type 4 represented by urbanization showed that urban areas slightly augmented by the encroachment of natural grasslands. Afforestation (D5) of pine and eucalyptus species had a higher increase, but implied a low percentage of change, at the expenses of natural grasslands. Natural processes, dynamic type 6, set diverse type of changes, highlighting the disappearance of nival zones (reduction of 87.51%), boosting the expansion of sparsely vegetated areas.

Table 1

Type of changes and dynamics occurred between 2000 and 2013 in the study area

Code	Land-change dynamic	Type of change	Change (km^2)	Change (%)
D1	Agricultural expansion	Low forest to Agricultural areas	138.4	1.7
		Shrublands to Agricultural areas	361.3	4.4
		Natural grasslands to Agricultural areas	2498.7	30.5
D2	Agricultural de-intensification	Agricultural areas to Natural grasslands	319.3	3.9
		Agricultural areas to Shrublands	1354.4	16.5
D3	Deforestation	Low forest to Shrublands	1023.6	12.5
D4	Urbanization	Natural grasslands to Continuous urban fabric	10.7	0.1
D5	Afforestation	Natural grasslands to Forest plantations	79.1	1.0
D6	Natural processes	Miscellaneous	2409.7	29.4
		Total	8192.8	100

Five types of clusters were delimited for dynamics of LULC changes over 2000 and 2013 (Fig 3). The bundle type 1 (ΔCH=26%), characterized four provinces with a dominant process of agricultural de-intensification combined with agricultural expansion and deforestation. Three provinces (cluster DB2, ΔCH=21%) were mainly controlled for natural processes, highlighting glaciers retreat and shrublands recovery. The third bunch (DB3) considered six provinces practically undisturbed. Whereas, group type 4 (DB4), displayed three provinces that experienced the biggest LULC changes (ΔCH=39%), due to deforestation, agricultural de-intensification and agricultural expansion. The fifth bundle (DB5, ΔCH=12%) defined nine provinces by its agricultural expansion. It should be noted that urbanization (D5) and afforestation (D6) had very short percentage of changed land, graphically imperceptible in each star plot (Fig 3).

Bundles of ES trends and relationships among individual ES trends

Cluster analysis defined four groups based on ES potential average trends of each province boundary over time (Fig 4). The bundle type 1, ESB1 revealed that thirteen provinces (67% of the study area) had a slight loss in regulating services and a constant supply of provisioning services over time. Four provinces (Bundle ESB2) experienced an improvement of regulating services and a reduction of provisioning. The positive changes occurred under a trajectory of land abandonment and fallowing. Bundle ESB3 showed six provinces with an overall change that had negative effects on regulating services, reducing to a greater extend water purification and regulation of soil erosion, mainly by the transformation of 1008 km^2 (mainly natural grassland areas). The fourth bundle (ESB4) characterised two provinces that enlarged its potential of provisioning services and soil quality. Water flow regulation potential denoted a significant reduction caused by the melting of glaciers (433 Km^2).

At phytoregion scale, the type and strength of the interactions among ES trends over 2000 and 2013 are detailed in Table S2 (Online Resource 1). Regulating services correlations were strongly positive. Trade-offs appeared with high strength among provisioning and regulating services, only soil quality and livestock had a moderate negative relationship. Crops and livestock services had a strong positive correlation. The twenty-one interactions were significantly ($p < 0.05$).

Associations between clusters of land-change dynamics and ecosystem service trends

Overlap and cluster analysis defined four links between land-change dynamics and ES trends (Fig 5). Group DES1 described provinces with an average of 29% of total change, characterizing areas by agricultural de-intensification (53% of the strength), that increased regulating services supply, despite deforestation activities. In this link, one province (La Mar) strongly dominated by land abandonment (DB1), as a quite unique force, had the highest increase of regulating services. Whereas, provinces described by type DB4 got a moderate increment due to the negative effect of deforestation and agricultural expansion.

Association type 2 (DES2, bundles DB2 and ESB4) involved two provinces highly induced by natural processes (69% of the total average change calculated by this link), that affected negatively water flow regulation and caused an augmentation of provisioning services and soil quality. It should be noted that increase of crops and livestock potential were as a consequence of glaciers retreat and expanding agricultural frontier.

The third link (DES3) associated thirteen provinces (ESB1) with an assortment of dynamic bundle types (DB1, DB2, DB3 and DB5), mainly defined by a slight decrease in regulating services, livestock and a low positive variation of crops provision. The average of total change for this link was 11%, however, there were two provinces (Vilcas Huaman and Tayacaja) with higher change ratio (32 and 24) described by a combination of almost equal forces of agricultural de-intensification and intensification. Associations between DB5 and ESB1 were marked by a low growth of farming in large provinces. One province with

19% of change due to natural processes (recovery of shrublands in grassland areas). The remaining areas (DB3) developed a pattern of minor transformations with an average of 3%.
Six provinces formed the fourth group (DES4) characterised by a positive supply of provisioning services and negative provision of regulating services (ESB3) obtained with a change average of 19%. The landscape mainly had the influence of agricultural expansion for bundle DB5 with deforestation and agricultural de-intensification in one province DB4 (Acobamba) that experience the largest alteration (47% of land-change).
At regional scale, the 79% of the changes indicated a territory with development of crops provision mainly caused by agricultural expansion. However, 19% of landscape variations had a positive tendency of WP, RSE, WFR and GCR due to land abandonment and/or fallowing; while 39% of area transformations got a growth in potential supply of cattle as a result of agricultural development; and 29% of zones presented an improvement in soil quality marked by farming de-intensification and natural processes.
The redundancy analysis (RDA) revealed that land-change dynamics model had a high capacity for predicting the variability of ES within each province (R^2=0.922 and P-value <0.001). In order to its partial contribution, the significant dynamics were: agricultural de-intensification (Akaike Information Criterion (AIC)= -75.155 and P-value <0.01), agricultural expansion (AIC= -81.813 and P-value <0.01), natural processes (AIC= -106.763 and P-value <0.01), urbanization (AIC= -114.233 and P-value <0.05) and deforestation (AIC= -116.563 and P-value <0.05). Afforestation had insignificant influence in the distribution of individual services.

Determinants for dynamics and ecosystem services

The RDA specified firewood, rural population and mining as the relevant variables that finest explicated the significant model generated by land-change dynamics and ES trends, R^2=0.37 and P-value <0.01. Each explanatory variable displayed different spatial distribution within the study area (Fig S1 in Online Resource 1). Firewood consumption had a negative trend in all the provinces, showing three different levels related to the departmental boundaries. In contrast, the percentage of mining concession areas presented an expansion in all the moist Puna. Rural population density characterised a territory with ten provinces in a growing rate and fifteen provinces with a decline percentage.
Fig S2 (Online Resource 1) plot (scaling 2) the RDA results for land-change dynamics and ES trends across the moist Puna. Provinces that experience an increase of regulating services and a reduction of provisioning (DES1) were related to areas with very low percentage of mining concessions, stable rural population growth and low reduction of firewood use. Provinces with an augmentation of provisioning services (DES2) and a highly reduction in water flow regulation stayed in areas with high percentage of mining and medium-high rural depopulation. Most of the provinces with very low changes in ES provision (DES3) had rural migration and low-medium increment in the mining activity. Provinces (DES4) mainly characterised for a decrease in regulating services and a slight increase in provision of livestock and crops had a medium mining activity and rural population growth.

Discussion

The involvement of 63 national and international experts with recognized experience developing ecological studies in the research field and being free to fulfil only the well-known LULC/regulating ES connections increased the confidence. The starting list of experts was short and grew by their suggestions as a “snow ball” sampling technique(Patton, 2002), taking the example by Scolozzi et al.(Scolozzi et al., 2012). Nevertheless, the final respondent pool was carefully selected from the larger number of qualified references following the indications by Jacobs et al.(Jacobs et al., 2015). This strategy assured a high rate of participation (68%, 43 experts were interviewed) in a low period (07 weeks). Finally, after removing outliers, an average of 39 interventions was computed getting low variability in the final scores and reaching a stable mean, in concordance with Campagne et al.(Campagne et al., 2017), and validated by the results of the sensitivity analysis.
Expert favourably scored low forest and peatbogs and high-Andean wetlands, in a certain way expressing comparable opinions with specialists from around the world(Burkhard et al., 2014; Depellegrin et al., 2016; Montoya-Tangarife et al., 2017). On the contrary, urban zones were scored as low as possible for many of the experts, coinciding with results from matrix model international studies(Bhandari et al., 2016; Burkhard et al., 2012, 2014; Sohel et al., 2015). Agricultural areas got medium-low potential supply showing similar analyses pointed, in other studies(Affek & Kowalska, 2017; Koschke et al., 2012). Glaciers and water bodies were highlighted as water flow controllers matching scores from Burkhard et al.(Burkhard et al., 2014). Forest plantations had medium-high attention from experts, these scores were slightly higher from the ones expressed by Montoya-

Tangarife et al.(Montoya-Tangarife et al., 2017) with identical species. Natural grasslands and shrublands develop important functions in the study area by its nature and spatial magnitude, as concerned by the practised.
At regional scale, the ES matrix captured a landscape with a richness in regulating services differing from the scores of provisioning services, that according to official studies, presented a region with medium-low potential for crops and livestock.
Cluster analysis for LULC changes confirmed that most of the provinces were mainly described by a small set of dynamics, but with one dominant force. Only one bundle that included the biggest LULC changes (DB4) was rather specialized in three dynamics. Three clusters were characterised by human actions and one by natural processes, just the bundle with the lowest ratio of change (DB3) had a quite diverse combination of forces. Urbanization and afforestation affected the lowest number of zones. Land-change dynamics described in the clusters are consistent with the stated in other regional studies(Aide et al., 2013; Brandt & Townsend, 2006; Pestalozzi, 2000; Tovar et al., 2013; K. R. Young, 2009).
Change over time analysis in pairwise interactions among ES described a strong significant correlation, revealing trade-offs among provisioning and regulating services; and synergies concerning the same ES sector. At similar landscapes, livestock trade-off global climate regulation, water flow regulation(Pan et al., 2014) and regulation of soil erosion(Petz et al., 2014). Turner et al.(K. G. Turner et al., 2014) assessed a strong relationship between provisioning services (crops and livestock) and negative interaction with water purification. In an agricultural landscape, a pattern of trade-offs was found between provisioning and regulating ecosystem services (C Raudsepp-Hearne et al., 2010). Agudelo-Patiño and Miralles-Garcia(Agudelo-Patiño & Miralles i Garcia, 2015) indicated that provision of crops compromised water flow regulation in an Andean urban mountain system.
ES bundles showed four different trends that linked the five land-change clusters establishing four types of associations. Link DES1 displayed four provinces that increased regulating ES potential due to an important process of agricultural de-intensification (46% of the total change caused by this dynamic in the moist Puna), despite the transformation of large areas of low forest to shrublands. Expert values denoted low differences between the ES potential supply of these last two LULC units. Farming reduction and deforestation co-occurred with a medium intensity of afforestation and a very small increase of farming land (25% and 9% of the total change caused by each dynamic in the moist Puna, respectively). The abandonment of marginal agricultural lands facilitates ecosystem recovery(Aide & Grau, 2004). Loss of soil fertility indicates shrublands regeneration(Rubiano et al., 2017). Evergreen vegetation regrows in natural fallow lands controlling soil erosion(Aguilera et al., 2013). Abandoned pastures and afforestation contribute to C-sequestration(Knoke et al., 2014).
Association DES2 described two provinces with high loss of water flow regulation and expansion of provisioning services due to glaciers retreat. In Peru, loss in surface area of glaciers is manifested in the last two decades(Rabatel et al., 2013) that may impact on water resources(López-Moreno et al., 2014) and arise land for grazing and farming (K. R. Young, 2014). DES2 showed an increment in soil quality produced by the conversion of agricultural areas to shrublands. One province (Yauli), situated in the north of the study area, was highly affected by urbanization (46% of the total change caused by this dynamic in the moist Puna) having an adverse influence on regulating and provisioning services. Urbanization has negative effects on water infiltration(Agudelo-Patiño & Miralles i Garcia, 2015) initiating surface run-off(Nakayama et al., 2007) and losses of carbon stocks and crops(Eigenbrod et al., 2011).
The expansion of agriculture was the dominant dynamic in association DES3 and DES4, characterising nineteen provinces (85% percent of the territory). In the case of DES3, a very low decrease in regulating services and livestock was assessed. This landscape was the less undisturbed over time. Whereas, provinces DES4 had an enlargement of provisioning services and a high reduction of regulating ES (accumulated the 33% and 29% of the total change caused by agricultural expansion and deforestation, respectively). Appropriate climatic conditions support crop development in higher elevation areas(Postigo, 2014) affecting natural grasslands that could reduce water flow regulation and livestock services(Rolando, Turin, et al., 2017).
Local social-ecological determinants explained where changes in associations of land-change dynamics and ES trends occurred across the moist Puna. Provinces (DES1) characterised by an increase in regulating services were related to a stable country population growth and a low fall of firewood consumption, whereas landscapes dominated by agricultural expansion were associated with the development of the countryside.

Areas (DES2) distinguished by a great loss of regulating services were associated with zones impacted by extraction activities. Provinces defined by a very low change in ES provision (DES3) were correlated to a great fall of rural population.

Our study focuses on cluster analysis over time on a provincial scale, since in Peru land planning at local level is regulated by provincial municipalities (Organic Law of Municipalities No. 27972, 27 of May of 2003). The integration of ES in planning depends on the governmental planning instruments(Albert et al., 2014), therefore our study might promote and facilitate the incorporation of ES at multiple scales. Furthermore, in relation to the temporal scale of 14 years, the tendency of changes occurred as consequences of land management activities were observable in the territory. However, long historical data can improve the understanding of ES dynamics(Egarter Vigl et al., 2017; Lautenbach et al., 2011; Renard et al., 2015), but in the study area, availability and quality of past LULC models are absent. Overall, our analysis addressed agricultural de-intensification, agricultural expansion, natural processes, urbanization and deforestation as the most critical land-change dynamics and its grouping across the high-Andean region over time. These clusters configured four types of ES bundles that might clarify ES complexity and help management purposes and decision-making.

The results have demonstrated that different patterns of land-change dynamics can have the same influence on the ES bundle development. The transformation of large areas is not necessarily equivalent to high variations in ES supply, whereas small land alterations are corresponding to slight impacts in ES provision. Moreover, trend mapping as expressed by Van Jaarsveld et al.(Van Jaarsveld et al., 2005) is suitable for measuring modifications in ES supply, based on LULC differences(Egarter Vigl et al., 2017). Lastly, the approach grounded on an expert-based ES matrix emphasising the competence of the methodology in locations with data scarcity.

Methods

Study area

The study is focusing on the phytoregion of the moist Puna comprised within the administrative boundaries of 25 provinces in the departments of Junín, Huancavelica and Ayacucho (Fig 1). The population at the end of 2015 was estimated as 2 055,758. Provincial area ranged from 724 to 10,999 km^2 with an average of 2561 km^2. Its geography is characterised by high plateaux and inter-Andean valleys (3500 m.a.s.l.) with a vegetation dominated for natural grasslands and shrublands(Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a). Human interventions at work have been done during several millennia(K. R. Young, 2009) configuring agro-ecosystems based in an extensive livestock rearing and smallholdings of Andean crops(Dixon, John; Gulliver, Aidan; Gibbon, David; Hall, 2001).

Data set

The study quantified the changes on the provision of ES over the interval of 14 y, from 2000 to 2013, using a selection of LULC types included in the standardized nomenclature of the Corine Land Cover (CLC) for Peru. This nomenclature adapted from the European Commission CORINE programme is based on a 3-level hierarchical classification system comprising 43 land-cover classes at its most detailed level, 16 classes at level II and five classes at level I. Mainly, the spatial data set was derived from two sources, map of high-Andean ecosystems in 2000(Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009a) and the official flora cover map from 2013(Ministry of Environment, 2015a). Both are polygon shapefiles generated in a mapping scale of 1:100,000 with Landsat (TM) images. Eleven relevant LULC were identified in the study area (Fig 1), only one (agricultural areas) is a class I due to coarse attributes. Table S3 in Online Resource 1 presents the features of the two-time step data sources and its harmonization to extract the research LULC. Therefore, the “intersect” and “dissolve” tools in ArcGIS 10.3.(ESRI, 2014) were used to improve the integration of data for the two-time step LULC maps in a polygon shapefile prepared for expert-based ES evaluation.

Ecosystem services matrix

The ES matrix is an expert-based estimation technique(Burkhard et al., 2009) that is extensively used to overcome data scarcity(Depellegrin et al., 2016; Montoya-Tangarife et al., 2017). However, uncertainties are included in the scoring assessment(Hou et al., 2013; Jacobs et al., 2015). In order to avoid this, Campagne et al.(Campagne et al., 2017) measured that 30 experts are enough to get a stable mean without inconsistencies and the variability of the final scores is constant after 15 experts, decreasing the standard error when increasing the expert panel size. For this study, 43 national and international experts (see respondent pool particulars in Online Resource 1), that have published scientific or technical works about ES or related ecological processes in the moist Puna, were individually consulted to rank the ES potential supply associated with a specific LULC on a relative scale, ranging from 0 (no relevant ES potential supply) up to 5 (very high ES potential supply). Burkhard et al.(Burkhard et al.,

2012) conceptualize the ES potential as the hypothetical maximum capacity of a LULC to supply a specific ES. Our matrix linked eleven LULC classes and seven ES, including regulating (n = 5) and provisioning (n = 2). To increase confidence, experts fulfilled only the LULC/regulating ES pairs that were surely in their judgments. Each response was collected and deprived of outliers using the interquartile range method (see Table S5, Online Resource 1). Then, a final score was computed using the mean. The potential supply of the LULC in provisioning services was achieved from official model results (see Table S6, Online Resource 1).

A sensitivity analysis was performed using descriptive statistics to prove the robustness of the regulating ES matrix. The standard deviation (SD) and the standard error (SE) were calculated from expert scores with the intention of ascertaining variability of the responses and uncertainty around the mean values, respectively. For variability control, given that match expert scores denote null SD, the answers were ranked in two categories, very low variability for SD ≤1 and low variability for SD higher than 1 and lower than 2. On the other hand, the uncertainty assessment was completed developing two sensitivity matrices with the expert scores ± SE (matrix 1 with expert scores +SE and matrix 2 with expert scores – SE). The kappa values were computed to obtain the degree of agreement between the ES regulating matrix and the sensitivity matrices.

Assessing the changes for LULC dynamics and ecosystem services

Initially, LULC changes from 2000 to 2013 were detected, showing the quantity of land that was converted from each LULC to any other. Furthermore, the consistencies were evaluated with kappa statistics(Cohen, 1960; Landis & Koch, 1977). The transitions assessed were grouped in main dynamics and its division at province scale were estimated with Excel 2015.

Secondly, cluster analysis was computed for land-change dynamics and ES trends supply. Clusters of dynamics (DB) were delineated with the percentage of LULC change accounted for the dynamics in each administrative boundary. Then, ES bundles were defined with the ES potential average change of each province boundary over 2000 and 2013. The optimal number of partitions for both cluster models was found with “affinity propagation” method(Frey & Dueck, 2007) using R(R Development Core Team, 2016). Bundle models were mapped with ArcGIS 10.3.(ESRI, 2014).

The relationships between individual pairs of ES (n=21 pairs) over 2000 and 2013 were achieved with Spearman's rho using the ES trend values. Significant correlation ($p < 0.05$) in negative relationships indicated trade-offs, whereas positive interactions were defined as synergies.

Thirdly, to assess the links between clusters of land-change dynamics and bundles of ES trends, the spatial correspondence between the two models was assessed by overlap analysis. Then, we gathered the overlapped clusters according to the number of partitions obtained with “affinity propagation” method(Frey & Dueck, 2007) using R(R Development Core Team, 2016).

Lastly, the land-change dynamics that best explained the variation of ES were determined using RDA (“vegan” R package and the function “ordistep”(Mulvaney et al., 2012)).

Identifying drivers for dynamics and ecosystem services

In our case study, RDA was computed for land-change dynamics and ES trends. The evaluation determined how land-change dynamics and ES trends were related to seven potential drivers (rural and urban population, mining, alpacas, goats, firewood and slope). These drivers were selected due to its role as explanatory variables used for dynamics or ES modelling. Deforestation in the moist Puna is related to anthropic actions like felling, firewood, fire and goat overgrazing(Naturserve, 2009). Depopulation of rural zones explain agricultural abandonment(Aide & Grau, 2004). Urban population growing increase town areas affecting many ecosystem services. Slope is negative relate to livestock and crops services(Meacham et al., 2016). Mining claims have consequences on Andean ecosystems and especially on water quality(B. E. Young et al., 2008).

RDA was calculated using the “vegan” R package and the function “ordistep”(Mulvaney et al., 2012), in order to obtain the best significant model (combination of explanatory variables), after 10,000 permutations (Legendre, 2018). Trend values for each driver were achieved as the differences between the values for the years 2000 and 2013 from census data, mining database and physiography model (the details of methods and data collection of drivers are in Table S7 Online Resources 1).

Data Availability

All data generated or analysed during this study are included in this published article (and its Supplementary Information file)

References

Abson, D. J., von Wehrden, H., Baumgärtner, S., Fischer, J., Hanspach, J., Härdtle, W., Heinrichs, H., Klein, A. M., Lang, D. J., Martens, P., & Walmsley, D. (2014). Ecosystem services as a boundary object for

sustainability. *Ecological Economics*, *103*, 29–37. https://doi.org/10.1016/j.ecolecon.2014.04.012
Affek, A. N., & Kowalska, A. (2017). Ecosystem potentials to provide services in the view of direct users. *Ecosystem Services*, *26*, 183–196. https://doi.org/10.1016/j.ecoser.2017.06.017
Agudelo-Patiño, L. C., & Miralles i Garcia, J. L. (2015). Design and management of the metropolitan green belt of Aburrá Valley, Colombia. *The Sustainable City X*, *1*, 193–203. https://doi.org/10.2495/sc150181
Aguilera, J., Motavalli, P., Valdivia, C., & Gonzales, M. A. (2013). Impacts of Cultivation and Fallow Length on Soil Carbon and Nitrogen Availability in the Bolivian Andean Highland Region. *Mountain Research and Development*, *33*(4), 391–403. https://doi.org/10.1659/MRD-JOURNAL-D-12-00077.1
Aide, T. M., Clark, M. L., Grau, H. R., López-Carr, D., Levy, M. A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M. J., & Muñiz, M. (2013). Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). *Biotropica*, *45*(2), 262–271. https://doi.org/10.1111/j.1744-7429.2012.00908.x
Aide, T. M., & Grau, H. R. (2004). Globalization, migration, and latin american ecosystems. In *Science* (Vol. 305, Issue 5692, pp. 1915–1916). https://doi.org/10.1126/science.1103179
Albert, C., Aronson, J., Fürst, C., & Opdam, P. (2014, October 10). Integrating ecosystem services in landscape planning: requirements, approaches, and impacts. *Landscape Ecology*, *29*(8), 1277–1285. https://doi.org/10.1007/s10980-014-0085-0
Anselm, N., Brokamp, G., & Schütt, B. (2018). Assessment of Land Cover Change in Peri-Urban High Andean Environments South of Bogotá, Colombia. *Land*, *7*(2), 75. https://doi.org/10.3390/land7020075
Balthazar, V., Vanacker, V., Molina, A., & Lambin, E. F. (2015). Impacts of forest cover change on ecosystem services in high Andean mountains. *Ecological Indicators*, *48*, 63–75. https://doi.org/10.1016/j.ecolind.2014.07.043
Baraer, M., Mckenzie, J. M., Mark, B. G., Bury, J., & Knox, S. (2009). Characterizing contributions of glacier melt and groundwater during the dry season in a poorly gauged catchment of the Cordillera Blanca (Peru). In *Adv. Geosci* (Vol. 22). www.adv-geosci.net/22/41/2009/
Bhandari, P., KC, M., Shrestha, S., Aryal, A., & Shrestha, U. B. (2016). Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal. *Applied Geography*, *69*, 25–34. https://doi.org/10.1016/j.apgeog.2016.02.003
Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Früh-Müller, A., Machnikowski, F., Mader, V. L., Nilsson, L., Sasaki, K., Rundlöf, M., Wolters, V., & Smith, H. G. (2015). Ecosystem services-current challenges and opportunities for ecological research. *Frontiers in Ecology and Evolution*, *2*(JAN). https://doi.org/10.3389/fevo.2014.00087
Blancas, A. N. I., Torre-Cuadros, M. de los Á. La, & Carrera, G. A. M. (2018). Using Foresight to Gain a Local Perspective on the Future of Ecosystem Services in a Mountain Protected Area in Peru. *Mountain Research and Development*, *38*(3), 192–202. https://doi.org/10.1659/mrd-journal-d-17-00090.1
Boillat, S., Scarpa, F. M., Robson, J. P., Gasparri, I., Aide, T. M., Aguiar, A. P. D., Anderson, L. O., Batistella, M., Fonseca, M. G., Futemma, C., Grau, H. R., Mathez-Stiefel, S. L., Metzger, J. P., Ometto, J. P. H. B., Pedlowski, M. A., Perz, S. G., Robiglio, V., Soler, L., Vieira, I., & Brondizio, E. S. (2017). Land system science in Latin America: challenges and perspectives. In *Current Opinion in Environmental Sustainability* (Vols. 26–27, pp. 37–46). Elsevier. https://doi.org/10.1016/j.cosust.2017.01.015
Bolliger, J., & Mladenoff, D. J. (2005). Quantifying spatial classification uncertainties of the historical Wisconsin landscape (USA). *Ecography*, *28*(2), 141–156. https://doi.org/10.1111/j.0906-7590.2005.03955.x
Brandt, J. S., & Townsend, P. A. (2006). Land use - Land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. *Landscape Ecology*, *21*(4), 607–623. https://doi.org/10.1007/s10980-005-4120-z
Burkhard, B., Kandziora, M., Hou, Y., & Müller, F. (2014). Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landscape Online*, *34*(1), 1–32. https://doi.org/10.3097/LO.201434
Burkhard, B., Kroll, F., Müller, F., & Windhorst, W. (2009). Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments. *Landscape Online*, *15*(1), 1–22. https://doi.org/10.3097/LO.200915
Burkhard, B., Kroll, F., Nedkov, S., & Müller, F. (2012). Mapping ecosystem service supply, demand and

budgets. *Ecological Indicators*, *21*, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019
Campagne, C. S., Roche, P., Gosselin, F., Tschanz, L., & Tatoni, T. (2017). Expert-based ecosystem services capacity matrices: Dealing with scoring variability. *Ecological Indicators*, *79*, 63–72. https://doi.org/10.1016/j.ecolind.2017.03.043
Caycho-Ronco, J., Arias-Mesia, A., Oswald, A., Esprella-Elias, R., Rivera, A., F. Yumisaca, J., & Andrade-Piedra. (2009). Tecnologías sostenibles y su uso en la producción de papa en la región altoandina. *Revista Latinoamericana de La Papa*, *15*(1), 20–37.
Charrad, M., Ghazzali, N., Boiteau, V., & Maintainer, A. N. (2015). *NbClust Package for determining the best number of clusters*. https://cran.r-project.org/web/packages/NbClust/NbClust.pdf
Cochi Machaca, N., Condori, B., Pardo, A. R., Anthelme, F., Meneses, R. I., Weeda, C. E., & Perotto-Baldivieso, H. L. (2018). Effects of grazing pressure on plant species composition and water presence on bofedales in the Andes mountain range of Bolivia. *Mires and Peat*, *21*(15), 1–15. https://doi.org/10.19189/MaP.2017.OMB.303
Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10.1177/001316446002000104
Cord, A. F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., & Volk, M. (2017). Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. In *Ecosystem Services* (Vol. 28, pp. 264–272). Elsevier. https://doi.org/10.1016/j.ecoser.2017.07.012
Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F., Verkerk, P. J., & Lavorel, S. (2015). Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. *Journal of Applied Ecology*, *52*(5), 1145–1155. https://doi.org/10.1111/1365-2664.12502
Cui, F., Tang, H., Zhang, Q., Wang, B., & Dai, L. (2019). Integrating ecosystem services supply and demand into optimized management at different scales: A case study in Hulunbuir, China. *Ecosystem Services*, *39*. https://doi.org/10.1016/j.ecoser.2019.100984
Custodio, M., Chanamé, F., Pizarro, S., & Cruz, D. (2018). Quality of the aquatic environment and diversity of benthic macroinvertebrates of high Andean wetlands of the Junín region, Peru. *The Egyptian Journal of Aquatic Research*, *44*(3), 195–202. https://doi.org/10.1016/J.EJAR.2018.08.004
Dade, M. C., Mitchell, M. G. E., McAlpine, C. A., & Rhodes, J. R. (2019). Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. In *Ambio* (Vol. 48, Issue 10, pp. 1116–1128). Springer Netherlands. https://doi.org/10.1007/s13280-018-1127-7
de Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*(3), 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006
de Gruijter, J. J., Bierkens, M. F. P., Brus, D. J., & Knotters, M. (2006). Sampling for Natural Resource Monitoring. In *Sampling for Natural Resource Monitoring*. Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-33161-1
de Valença, A. W., Vanek, S. J., Meza, K., Ccanto, R., Olivera, E., Scurrah, M., Lantinga, E. A., & Fonte, S. J. (2017). Land use as a driver of soil fertility and biodiversity across an agricultural landscape in the Central Peruvian Andes. *Ecological Applications*, *27*(4), 1138–1154. https://doi.org/10.1002/eap.1508
Deng, X., Li, Z., & Gibson, J. (2016). A review on trade-off analysis of ecosystem services for sustainable land-use management. In *Journal of Geographical Sciences* (Vol. 26, Issue 7, pp. 953–968). Science in China Press. https://doi.org/10.1007/s11442-016-1309-9
Depellegrin, D., Pereira, P., Misiunė, I., & Egarter-Vigl, L. (2016). Mapping ecosystem services potential in Lithuania. *International Journal of Sustainable Development and World Ecology*, *23*(5), 441–455. https://doi.org/10.1080/13504509.2016.1146176
der Biest Van, D'Hondt, R., Jacobs, S., Landuyt, D., Staes, J., Goethals, P., & Meire, P. (2014). EBI: An index for delivery of ecosystem service bundles. *Ecological Indicators*, *37*, *Part A*, 252–265. https://doi.org/10.1016/j.ecolind.2013.04.006
Dixon, John; Gulliver, Aidan; Gibbon, David; Hall, M. (2001). Farming Systems and Poverty Farming Systems and Poverty:Improving Farmers' Livelihoods in a Changing World. *FAO and World Bank, Rome and Washington DC*, 412. https://doi.org/10.1017/S0014479702211059
Dou, H., Li, X., Li, S., & Dang, D. (2018). How to Detect Scale Effect of Ecosystem Services Supply? A Comprehensive Insight from Xilinhot in Inner Mongolia, China. *Sustainability*, *10*(10), 3654.

https://doi.org/10.3390/su10103654
Du, X., Jin, X., Yang, X., Yang, X., & Zhou, Y. (2014). Spatial pattern of land use change and its driving force in Jiangsu province. *International Journal of Environmental Research and Public Health*, *11*(3), 3215–3232. https://doi.org/10.3390/ijerph110303215
Duchicela, S. A., Cuesta, F., Pinto, E., Gosling, W. D., & Young, K. R. (2019). Indicators for assessing tropical alpine rehabilitation practices. *Ecosphere*, *10*(2), e02595. https://doi.org/10.1002/ecs2.2595
Egarter Vigl, L., Tasser, E., Schirpke, U., & Tappeiner, U. (2017). Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. *Regional Environmental Change*, *17*(8), 2237–2250. https://doi.org/10.1007/s10113-017-1132-6
Egoh, B. N., Reyers, B., Rouget, M., & Richardson, D. M. (2011). Identifying priority areas for ecosystem service management in South African grasslands. *Journal of Environmental Management*, *92*(6), 1642–1650. https://doi.org/10.1016/j.jenvman.2011.01.019
Eigenbrod, F., Bell, V. A., Davies, H. N., Heinemeyer, A., Armsworth, P. R., & Gaston, K. J. (2011). The impact of projected increases in urbanization on ecosystem services. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1722), 3201–3208. https://doi.org/10.1098/rspb.2010.2754
Ektvedt, T. M., Vetaas, O. R., & Lundberg, A. (2012). Land-cover changes during the past 50 years in the semi-arid tropical forest region of northern peru. *Erdkunde*, *66*(1), 57–75. https://doi.org/10.3112/erdkunde.2012.01.05
ESRI. (2014). ArcGIS Desktop: Release 10.3. In *Redlands CA* (p. Environmental Systems Research Institute.). https://doi.org/10.1209/epl/i2001-00551-4
European Environment Agency. (2013). *Common International Classification of Ecosystem Services (CICES)*. Cices. http://cices.eu/
Feixiang, S. U. N., Yihe, L. Y. U., Bojie, F. U., & Jian, H. U. (2016). Hydrological Services by Mountain Ecosystems in Qilian Mountain of China : A Review. *Chinese Geographical Science*, *26*(2), 174–187. https://doi.org/10.1007/s11769-015-0791-9
Felipe-Lucia, M. R., Comín, F. A., & Bennett, E. M. (2014). Interactions Among Ecosystem Services Across Land Uses in a Floodplain Agroecosystem. *Ecology and Society*, *19*(1), art20. https://doi.org/10.5751/ES-06249-190120
Fjeldså, J. (2002). Polylepis forests – vestiges of a vanishing ecosystem in the Andes. *Ecotropica*, *8*, 111–123.
Fonte, S. J., Vanek, S. J., Oyarzun, P., Parsa, S., Quintero, D. C., Rao, I. M., & Lavelle, P. (2012). Pathways to Agroecological Intensification of Soil Fertility Management by Smallholder Farmers in the Andean Highlands. In *Advances in Agronomy* (Vol. 116, pp. 125–184). https://doi.org/10.1016/B978-0-12-394277-7.00004-X
Frey, B. J., & Dueck, D. (2007). Clustering by passing messages between data points. *Science*, *315*(5814), 972–976. https://doi.org/10.1126/science.1136800
Geist, H. J., & Lambin, E. F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience*, *52*(2), 143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:pcaudf]2.0.co;2
Geological Mining and Metallurgical Institute. (2018). *Mapa catastro minero del Perú* (p. 1).
Gibbon, A., Silman, M. R., Malhi, Y., Fisher, J. B., Meir, P., Zimmermann, M., Dargie, G. C., Farfan, W. R., & Garcia, K. C. (2010). Ecosystem Carbon Storage Across the Grassland–Forest Transition in the High Andes of Manu National Park, Peru. *Ecosystems*, *13*(7), 1097–1111. https://doi.org/10.1007/s10021-010-9376-8
Gobierno Regional de Ayacucho. (2013). *Zonificación Ecológica Económica - Ayacucho*.
Gobierno Regional de Huancavelica. (2013). *MESO ZONIFICACION ECOLOGICA y ECONOMICA DEL DEPARTAMENTO DE HUANCAVELICA*.
Grêt-Regamey, A., Brunner, S. H., & Kienast, F. (2012). Mountain Ecosystem Services: Who Cares? *Mountain Research and Development*, *32*(S1), S23–S34. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1
Gutiérrez B., N., Gärtner, S., López H., J. Y., Pacheco, C. E., & Reif, A. (2013). The recovery of the lower montane cloud forest in the Mucujún watershed, Mérida, Venezuela. *Regional Environmental Change*, *13*(5), 1069–1085. https://doi.org/10.1007/s10113-013-0413-y
Haines-Young, R., & Potschin, M. (2018). CICES V5. 1. Guidance on the Application of the Revised Structure. *Fabis Consulting*, *January*, 53. www.cices.eu

Haller, A. (2012). Vivid valleys, pallid peaks? Hypsometric variations and rural-urban land change in the Central Peruvian Andes. *Applied Geography*, *35*(1–2), 439–447. https://doi.org/10.1016/j.apgeog.2012.09.009

Haller, A., & Borsdorf, A. (2013). Huancayo Metropolitano. *Cities*, *31*, 553–562. https://doi.org/10.1016/J.CITIES.2012.04.004

Hamann, M., Biggs, R., & Reyers, B. (2015). Mapping social-ecological systems: Identifying "green-loop" and "red-loop" dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change*, *34*, 218–226. https://doi.org/10.1016/j.gloenvcha.2015.07.008

Hartman, B. D., Bookhagen, B., & Chadwick, O. A. (2016). The effects of check dams and other erosion control structures on the restoration of Andean bofedal ecosystems. *Restoration Ecology*, *24*(6), 761–772. https://doi.org/10.1111/rec.12402

Hein, L., van Koppen, C. S. A. K., van Ierland, E. C., & Leidekker, J. (2016). Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. *Ecosystem Services*, *21*, 109–119. https://doi.org/10.1016/j.ecoser.2016.07.008

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. In *Environmental Research Letters* (Vol. 7, Issue 4, p. 044009). IOP Publishing. https://doi.org/10.1088/1748-9326/7/4/044009

Hou, Y., Burkhard, B., & Müller, F. (2013). Uncertainties in landscape analysis and ecosystem service assessment. *Journal of Environmental Management*, *127*, S117–S131. https://doi.org/10.1016/j.jenvman.2012.12.002

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*(1), 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

INEI - National Institute of Statistics and Informatics. (n.d.-a). *III Censo Nacional Agropecuario 1994 (III CENAGRO)*. http://censos.inei.gob.pe/bcoCuadros/IIIcenagro.htm

INEI - National Institute of Statistics and Informatics. (n.d.-b). *National census*. https://www.inei.gob.pe/estadisticas/censos/

INEI - National Institute of Statistics and Informatics. (2014). *Encuesta Nacional de Hogares*. https://webinei.inei.gob.pe/anda_inei/index.php/catalog/ENC_HOGARES

Jacobs, S., Burkhard, B., Van Daele, T., Staes, J., & Schneiders, A. (2015). 'The Matrix Reloaded': A review of expert knowledge use for mapping ecosystem services. *Ecological Modelling*, *295*, 21–30. https://doi.org/10.1016/j.ecolmodel.2014.08.024

Jameson, J. S., & Ramsay, P. M. (2007). Changes in high-altitude Polylepis forest cover and quality in the Cordillera de Vilcanota, Perú, 1956–2005. *Biological Conservation*, *138*(1–2), 38–46. https://doi.org/10.1016/J.BIOCON.2007.04.008

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., Chacón-Moreno, E., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009). *Ecosistemas de los Andes del Norte y Centro*. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. http://www.saber.ula.ve/handle/123456789/39336

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009a). *Ecosistemas de los Andes del Norte y Centro*. Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL. Lima. pp.7-9. https://doi.org/10.1164/rccm.200702-271OC

Josse, C., Cuesta, F., Navarro, G., Barrena, V., Cabrera, E., E, C.-M., Ferreira, W., Peralvo, M., Saito, J., & Tovar, A. (2009b). *Mapa de ecosistemas de los andes del norte y centro. Bolivia,Colombia, Ecuador, Perú y Venezuela*. www.infoandina.org/ecosistemasandinos

Knoke, T., Bendix, J., Pohle, P., Hamer, U., Hildebrandt, P., Roos, K., Gerique, A., Sandoval, M. L., Breuer, L., Tischer, A., Silva, B., Calvas, B., Aguirre, N., Castro, L. M., Windhorst, D., Weber, M., Stimm, B., Günter, S., Palomeque, X., … Beck, E. (2014). Afforestation or intense pasturing improve the ecological and economic value of abandoned tropical farmlands. *Nature Communications*, *5*. https://doi.org/10.1038/ncomms6612

Koschke, L., Fürst, C., Frank, S., & Makeschin, F. (2012). A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecological*

Indicators, *21*, 54–66. https://doi.org/10.1016/j.ecolind.2011.12.010
Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M. R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P. J., Verburg, P. H., & Reenberg, A. (2016). Hotspots of land use change in Europe. *Environmental Research Letters*, *11*(6), 064020. https://doi.org/10.1088/1748-9326/11/6/064020
Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, *28*(1), 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459
Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. *Biometrics*, *33*(1), 159. https://doi.org/10.2307/2529310
Lautenbach, S., Kugel, C., Lausch, A., & Seppelt, R. (2011). Analysis of historic changes in regional ecosystem service provisioning using land use data. *Ecological Indicators*, *11*(2), 676–687. https://doi.org/10.1016/j.ecolind.2010.09.007
Lavorel, S., Bayer, A., Bondeau, A., Lautenbach, S., Ruiz-Frau, A., Schulp, N., Seppelt, R., Verburg, P., Teeffelen, A. van, Vannier, C., Arneth, A., Cramer, W., & Marba, N. (2017). Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. In *Ecological Indicators* (Vol. 74, pp. 241–260). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2016.11.015
Lee, E., Livino, A., Han, S. C., Zhang, K., Briscoe, J., Kelman, J., & Moorcroft, P. (2018). Land cover change explains the increasing discharge of the Paraná River. *Regional Environmental Change*, *18*(6), 1871–1881. https://doi.org/10.1007/s10113-018-1321-y
Lee, H., & Lautenbach, S. (2016). A quantitative review of relationships between ecosystem services. *Ecological Indicators*, *66*, 340–351. https://doi.org/10.1016/j.ecolind.2016.02.004
Legendre, P. (2018). Numerical ecology. In *Encyclopedia of Ecology* (pp. 487–493). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10595-0
Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M. R., Metzger, M. J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P. H., Verkerk, P. J., & Kuemmerle, T. (2018). Archetypical patterns and trajectories of land systems in Europe. *Regional Environmental Change*, *18*(3), 715–732. https://doi.org/10.1007/s10113-015-0907-x
Li, T., Lü, Y., Fu, B., Hu, W., & Comber, A. J. (2019). Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: enhanced services while depressed synergies. *Ecological Indicators*, *99*, 332–342. https://doi.org/10.1016/j.ecolind.2018.12.041
Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., & Li, S. (2015). Systems integration for global sustainability. In *Science* (Vol. 347, Issue 6225). https://doi.org/10.1126/science.1258832
Locatelli, B., Lavorel, S., Sloan, S., Tappeiner, U., & Geneletti, D. (2017). Characteristic trajectories of ecosystem services in mountains. In *Frontiers in Ecology and the Environment* (Vol. 15, Issue 3, pp. 150–159). Wiley-Blackwell. https://doi.org/10.1002/fee.1470
López-Moreno, J. I., Fontaneda, S., Bazo, J., Revuelto, J., Azorin-Molina, C., Valero-Garcés, B., Morán-Tejeda, E., Vicente-Serrano, S. M., Zubieta, R., & Alejo-Cochachín, J. (2014). Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. *Global and Planetary Change*, *112*, 1–11. https://doi.org/10.1016/j.gloplacha.2013.10.010
Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*(12), 2365–2407. https://doi.org/10.1080/0143116031000139863
MA. (2005). *Ecosystems and human well-being: synthesis report*. www.islandpress.org
Madrigal-Martínez, S., & Miralles i García, J. L. (2019a). Understanding land use changes in the central high-Andean moist Puna. *WIT Transactions on Ecology and the Environment*, *238*.
Madrigal-Martínez, S., & Miralles i García, J. L. (2019b). Land-change dynamics and ecosystem service trends across the central high-Andean Puna. *Scientific Reports*, *9*(1), 9688. https://doi.org/10.1038/s41598-019-46205-9
Maldonado Fonkén, M. S. (2014). An introduction to the bofedales of the Peruvian High Andes. *Mires and Peat*, *15*(15), 1–13. http://www.mires-and-peat.net/,ISSN1819-754X
Mark, B. G., & Seltzer, G. O. (2003). Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *Journal of Glaciology*, *49*(165), 271–281. https://doi.org/10.3189/172756503781830746
Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Del Amo, D. G., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I., Willaarts, B., González, J. A., Santos-Martín, F., Onaindia, M., López-Santiago, C., & Montes, C. (2012). Uncovering ecosystem service bundles through social preferences. *PLoS ONE*, *7*(6), e38970.

https://doi.org/10.1371/journal.pone.0038970
Meacham, M., Queiroz, C., Norström, A. V., & Peterson, G. D. (2016). Social-ecological drivers of multiple ecosystem services: What variables explain patterns of ecosystem services across the Norrström drainage basin? *Ecology and Society*, *21*(1). https://doi.org/10.5751/ES-08077-210114
Metzger, M. J., Rounsevell, M. D. A., van den Heiligenberg, H. A. R. M., Pérez-Soba, M., & Hardiman, P. S. (2010). How personal judgment influences scenario development: An example for future rural development in Europe. *Ecology and Society*, *15*(2), 27. https://doi.org/10.5751/ES-03305-150205
Ministry of Economy and Treasury. (n.d.). *Banco de Inversiones - invierte.pe*.
Ministry of Environment. (n.d.-a). *Geoservidor*. ZONIFICACIÓN ECOLÓGICA Y ECONÓMICA – ZEE. https://geoservidor.minam.gob.pe/zee-aprobadas/zee-aprobadas/
Ministry of Environment. (n.d.-b). *Mecanismos de retibucion por servicios ecosistemicos*. Retrieved October 4, 2019, from http://serviciosecosistemicos.minam.gob.pe/
Ministry of Environment. (2012). *Memoria descriptiva del mapa de cobertura vegetal del Peru*.
Ministry of Environment. (2014). *LA ESTRATEGIA NACIONAL DE DIVERSIDAD BIOLÓGICA AL 2021 Y SU PLAN DE ACCIÓN 2014-2018*.
Ministry of Environment. (2015a). *Mapa nacional de cobertura vegetal. Memoria descriptiva.* http://www.minam.gob.pe/patrimonio-natural/wp-content/uploads/sites/6/2013/10/MAPA-NACIONAL-DE-COBERTURA-VEGETAL-FINAL.compressed.pdf
Ministry of Environment. (2015b). *Mapa nacional de cobertura vegetal* (p. 1). Dirección General de Evaluación, Valoración y Financiamiento del Patrimonio Natural.
Ministry of Environment. (2017). *ESTADO SITUACIONAL DE LA ZONIFICACIÓN ECOLÓGICA Y ECONÓMICA (ZEE) A NIVEL REGIONAL.*
Ministry of Environment. (2018). *Mapa nacional de ecosistemas del Perú. Memoria Descriptiva*.
Ministry of Environment, & SERNANP. (2016). *ÁREAS NATURALES PROTEGIDAS DEL PERÚ Conservación para el desarrollo sostenible*.
Miranda, A., Altamirano, A., Cayuela, L., Pincheira, F., & Lara, A. (2015). Different times, same story: Native forest loss and landscape homogenization in three physiographical areas of south-central of Chile. *Applied Geography*, *60*, 20–28. https://doi.org/10.1016/j.apgeog.2015.02.016
Molina, A., Vanacker, V., Brisson, E., Mora, D., & Balthazar, V. (2015). Multidecadal change in streamflow associated with anthropogenic disturbances in the tropical Andes. *Hydrology and Earth System Sciences*, *19*(10), 4201–4213. https://doi.org/10.5194/hess-19-4201-2015
Montoya-Tangarife, C., de la Barrera, F., Salazar, A., & Inostroza, L. (2017). Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaíso, Chile. *PLOS ONE*, *12*(11), e0188117. https://doi.org/10.1371/journal.pone.0188117
Mouchet, M. A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., & Lavorel, S. (2014). An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Global Environmental Change*, *28*(1), 298–308. https://doi.org/10.1016/j.gloenvcha.2014.07.012
Mulvaney, D., Robbins, P., & Freeman, C. P. (2012). Vegan. In *Green Food: An A-to-Z Guide* (p. 2). https://doi.org/10.4135/9781412971874.n145
Nakayama, T., Watanabe, M., Tanji, K., & Morioka, T. (2007). Effect of underground urban structures on eutrophic coastal environment. *Science of the Total Environment*, *373*(1), 270–288. https://doi.org/10.1016/j.scitotenv.2006.11.033
National Institute of Natural Resources. (2000). *Mapa forestal del Perú* (p. 1). INRENA.
Naturserve. (2009). *International Ecological Classification Standard: Terrestrial Ecological Classifications. Sistemas Ecológicos de los Andes del Norte y Centro*.
Nelson, G. C., Bennett, E., Berhe, A. A., Cassman, K., DeFries, R., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., Levy, M., Marco, D., Nakicenovic, N., O'Neill, B., Norgaard, R., Petschel-Held, G., Ojima, D., Pingali, P., Watson, R., & Zurek, M. (2006). Anthropogenic drivers of ecosystem change: An overview. In *Ecology and Society* (Vol. 11, Issue 2, p. 29). https://doi.org/10.5751/ES-01826-110229
Oliveras, I., Girardin, C., Doughty, C. E., Cahuana, N., Arenas, C. E., Oliver, V., Huaraca Huasco, W., & Malhi, Y. (2014). Andean grasslands are as productive as tropical cloud forests. *Environmental Research Letters*, *9*(11), 115011. https://doi.org/10.1088/1748-9326/9/11/115011
Oscanoa, L., & Flores, E. (2016). INFLUENCIA DE TÉCNICAS DE MEJORA DE SUELOS SOBRE LA FUNCIÓN HÍDRICA DE PASTOS NATURALES ALTOANDINOS. *Ecología Aplicada*, *15*(2), 91. https://doi.org/10.21704/rea.v15i2.748
Pan, Y., Wu, J., & Xu, Z. (2014). Analysis of the tradeoffs between provisioning and regulating services

from the perspective of varied share of net primary production in an alpine grassland ecosystem. *Ecological Complexity*, *17*(1), 79–86. https://doi.org/10.1016/j.ecocom.2013.11.001

Patton, M. (2002). *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*.

Pestalozzi, H. (2000). Sectoral Fallow Systems and the Management of Soil Fertility: The Rationality of Indigenous Knowledge in the High Andes of Bolivia. *Mountain Research and Development*, *20*(1), 64–71. https://doi.org/http://dx.doi.org/10.1659/0276-4741(2000)020[0064:SFSATM]2.0.CO;2

Petz, K., Alkemade, R., Bakkenes, M., Schulp, C. J. E., van der Velde, M., & Leemans, R. (2014). Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Global Environmental Change*, *29*, 223–234. https://doi.org/10.1016/j.gloenvcha.2014.08.007

Postigo, J. C. (2014). Perception and Resilience of Andean Populations Facing Climate Change. *Journal of Ethnobiology*, *34*(3), 383–400. https://doi.org/10.2993/0278-0771-34.3.383

Qiao, X., Gu, Y., Zou, C., Xu, D., Wang, L., Ye, X., Yang, Y., & Huang, X. (2019). Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. *Science of the Total Environment*, *651*, 218–229. https://doi.org/10.1016/j.scitotenv.2018.09.135

Queiroz, C., Meacham, M., Richter, K., Norström, A. V., Andersson, E., Norberg, J., & Peterson, G. (2015). Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. *Ambio*, *44*(1), 89–101. https://doi.org/10.1007/s13280-014-0601-0

Quintero-Gallego, M. E., Quintero-Angel, M., & Vila-Ortega, J. J. (2018). Exploring land use/land cover change and drivers in Andean mountains in Colombia: A case in rural Quindío. *Science of the Total Environment*, *634*, 1288–1299. https://doi.org/10.1016/j.scitotenv.2018.03.359

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. In *R Foundation for Statistical Computing* (Vol. 1, Issue 2.11.1, p. 409). https://doi.org/10.1007/978-3-540-74686-7

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J. E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., … Wagnon, P. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere*, *7*(1), 81–102. https://doi.org/10.5194/tc-7-81-2013

Raudsepp-Hearne, C, Peterson, G. D., & Bennett, E. M. (2010). Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences*, *107*(11), 5242–5247. https://doi.org/10.1073/pnas.0907284107

Raudsepp-Hearne, Ciara, & Peterson, G. D. (2016). Scale and ecosystem services: How do observation, management, and analysis shift with scale—lessons from Québec. *Ecology and Society*, *21*(3), art16. https://doi.org/10.5751/ES-08605-210316

Renard, D., Rhemtulla, J. M., & Bennett, E. M. (2015). Historical dynamics in ecosystem service bundles. *Proceedings of the National Academy of Sciences*, *112*(43), 13411–13416. https://doi.org/10.1073/pnas.1502565112

Restrepo, J. D., Kettner, A. J., & Syvitski, J. P. M. (2015). Recent deforestation causes rapid increase in river sediment load in the Colombian Andes. *Anthropocene*, *10*, 13–28. https://doi.org/10.1016/j.ancene.2015.09.001

Rieb, J. T., Chaplin-Kramer, R., Daily, G. C., Armsworth, P. R., Böhning-Gaese, K., Bonn, A., Cumming, G. S., Eigenbrod, F., Grimm, V., Jackson, B. M., Marques, A., Pattanayak, S. K., Pereira, H. M., Peterson, G. D., Ricketts, T. H., Robinson, B. E., Schröter, M., Schulte, L. A., Seppelt, R., … Bennett, E. M. (2017). When, Where, and How Nature Matters for Ecosystem Services: Challenges for the Next Generation of Ecosystem Service Models. *BioScience*, *67*(9), 820–833. https://doi.org/10.1093/biosci/bix075

Roces-Díaz, J. V., Vayreda, J., Banqué-Casanovas, M., Díaz-Varela, E., Bonet, J. A., Brotons, L., De-Miguel, S., Herrando, S., & Martínez-Vilalta, J. (2018). The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships. *Science of the Total Environment*, *626*, 1270–1283. https://doi.org/10.1016/j.scitotenv.2018.01.150

Rodríguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., Dobson, A. P., & Peterson, G. D. (2006). Trade-offs across Space , Time , and Ecosystem Services. *Ecology and Society*, *11*(1). https://cals.arizona.edu/classes/ram696a/ES tradeoffs 2006.pdf

Rodríguez, L. C., Pascual, U., & Niemeyer, H. M. (2006). Local identification and valuation of ecosystem goods and services from Opuntia scrublands of Ayacucho, Peru. *Ecological Economics*, *57*(1), 30–

44. https://doi.org/10.1016/J.ECOLECON.2005.03.022
Rolando, J. L., Dubeux, J. C., Perez, W., Ramirez, D. A., Turin, C., Ruiz-Moreno, M., Comerford, N. B., Mares, V., Garcia, S., & Quiroz, R. (2017). Soil organic carbon stocks and fractionation under different land uses in the Peruvian high-Andean Puna. *Geoderma*, *307*, 65–72. https://doi.org/10.1016/j.geoderma.2017.07.037
Rolando, J. L., Turin, C., Ramírez, D. A., Mares, V., Monerris, J., & Quiroz, R. (2017). Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes. In *Agriculture, Ecosystems and Environment* (Vol. 236, pp. 221–233). Elsevier. https://doi.org/10.1016/j.agee.2016.12.010
Rounsevell, M. D. A., Pedroli, B., Erb, K. H., Gramberger, M., Busck, A. G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M. J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P. H., & Wolfslehner, B. (2012). Challenges for land system science. *Land Use Policy*, *29*(4), 899–910. https://doi.org/10.1016/j.landusepol.2012.01.007
Rubiano, K., Clerici, N., Norden, N., & Etter, A. (2017). Secondary forest and shrubland dynamics in a highly transformed landscape in the Northern Andes of Colombia (1985-2015). *Forests*, *8*(6). https://doi.org/10.3390/f8060216
Saavedra Briones, P., & Sepúlveda-Varas, A. (2016). SYSTEMATIC TRANSITIONS IN LAND USE AND LAND COVER IN A PRE-ANDEAN SUB-WATERSHED WITH HIGH HUMAN INTERVENTION IN THE ARAUCANIA REGION, CHILE. *Ciencia e Investigación Agraria*, *43*(3), 6–6. https://doi.org/10.4067/s0718-16202016000300006
Saidi, N., & Spray, C. (2018). Ecosystem services bundles: Challenges and opportunities for implementation and further research. In *Environmental Research Letters* (Vol. 13, Issue 11, p. 113001). IOP Publishing. https://doi.org/10.1088/1748-9326/aae5e0
Salvador, F., Monerris, J., & Rochefort, L. (2014). Peatlands of the Peruvian Puna ecoregion: types, characteristics and disturbance. *Mires and Peat*, *15*(3), 1–17. http://www.mires-and-peat.net/,
Scholes, R. J., Reyers, B., Biggs, R., Spierenburg, M. J., & Duriappah, A. (2013). Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issue 1, pp. 16–25). Elsevier. https://doi.org/10.1016/j.cosust.2013.01.004
Scolozzi, R., Morri, E., & Santolini, R. (2012). Delphi-based change assessment in ecosystem service values to support strategic spatial planning in Italian landscapes. *Ecological Indicators*, *21*, 134–144. https://doi.org/10.1016/j.ecolind.2011.07.019
Segnini, A., Posadas, A., Quiroz, R., Milori, D. M. B. P., Saab, S. C., Neto, L. M., & Vaz, C. M. P. (2010). Spectroscopic Assessment of Soil Organic Matter in Wetlands from the High Andes. *Soil Science Society of America Journal*, *74*(6), 2246. https://doi.org/10.2136/sssaj2009.0445
SERFOR. (n.d.). *Plataforma de seguimiento de la Zonificación Forestal (v1.1)*. Retrieved September 6, 2019, from https://datastudio.google.com/u/0/reporting/1rBWIgdSv6bgul4RaAyMnpnW9myR3t-sB/page/qCMh
SERNANP. (2019). *ÁREAS NATURALES PROTEGIDAS DE ADMINISTRACIÓN NACIONAL CON CATEGORIA DEFINITIVA*.
Skarbø, K., & VanderMolen, K. (2016). Maize migration: key crop expands to higher altitudes under climate change in the Andes. *Climate and Development*, *8*(3), 245–255. https://doi.org/10.1080/17565529.2015.1034234
Sohel, M. S. I., Ahmed Mukul, S., & Burkhard, B. (2015). Landscape's capacities to supply ecosystem services in Bangladesh: A mapping assessment for Lawachara National Park. *Ecosystem Services*, *12*, 128–135. https://doi.org/10.1016/j.ecoser.2014.11.015
Spake, R., Lasseur, R., Crouzat, E., Bullock, J. M., Lavorel, S., Parks, K. E., Schaafsma, M., Bennett, E. M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G. D., Schulp, C. J. E., Thuiller, W., Turner, M. G., Verburg, P. H., & Eigenbrod, F. (2017). Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. *Global Environmental Change*, *47*, 37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004
Stepputat, F., & Nyberg Sørensen, N. (2001). The rise and fall of "Internally Displaced People" in the Central Peruvian Andes. *Development and Change*, *32*(4), 769–791. https://doi.org/10.1111/1467-7660.00225
Stürck, J., & Verburg, P. H. (2017). Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. *Landscape Ecology*,

32(3), 481–500. https://doi.org/10.1007/s10980-016-0459-6
Swinton, S. M., & Quiroz, R. (2003). Poverty and the deterioration of natural soil capital in the Peruvian altiplano. *Environment, Development and Sustainability*, *5*(3–4), 477–490. https://doi.org/10.1023/A:1025785231559
Tito, R., Vasconcelos, H. L., & Feeley, K. J. (2018). Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. *Global Change Biology*, *24*(2), e592–e602. https://doi.org/10.1111/gcb.13959
Tomscha, S. A., & Gergel, S. E. (2016). Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecology and Society*, *21*(1), art43. https://doi.org/10.5751/ES-08345-210143
Tovar, C., Seijmonsbergen, A. C., & Duivenvoorden, J. F. (2013). Monitoring land use and land cover change in mountain regions: An example in the Jalca grasslands of the Peruvian Andes. *Landscape and Urban Planning*, *112*(1), 40–49. https://doi.org/10.1016/j.landurbplan.2012.12.003
Trabucchi, M., Comín, F. A., & O'Farrell, P. J. (2013). Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services. *Regional Environmental Change*, *13*(4), 911–926. https://doi.org/10.1007/s10113-012-0392-4
Turner, B. L. (2002). Toward Integrated Land-Change Science: Advances in 1.5 Decades of Sustained International Research on Land-Use and Land-Cover Change. In B. C. Steffen W., Jäger J., Carson D.J. (Ed.), *Challenges of a Changing Earth. Global Change — The IGBP Series* (pp. 21–26). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-19016-2_3
Turner, K. G., Odgaard, M. V., Bøcher, P. K., Dalgaard, T., & Svenning, J. C. (2014). Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landscape and Urban Planning*, *125*, 89–104. https://doi.org/10.1016/j.landurbplan.2014.02.007
Turner, M. G., O'Neill, R. V., Gardner, R. H., & Milne, B. T. (1989). Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecology*, *3*(3–4), 153–162. https://doi.org/10.1007/BF00131534
Vallet, A., Locatelli, B., Levrel, H., Wunder, S., Seppelt, R., Scholes, R. J., & Oszwald, J. (2018). Relationships Between Ecosystem Services: Comparing Methods for Assessing Tradeoffs and Synergies. *Ecological Economics*, *150*, 96–106. https://doi.org/10.1016/j.ecolecon.2018.04.002
Van Jaarsveld, A. S., Biggs, R., Scholes, R. J., Bohensky, E., Reyers, B., Lynam, T., Musvoto, C., & Fabricius, C. (2005). Measuring conditions and trends in ecosystem services at multiple scales: The Southern African Millennium Ecosystem Assessment (SAfMA) experience. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 425–441. https://doi.org/10.1098/rstb.2004.1594
Vásquez, E., Ladd, B., & Borchard, N. (2014). Carbon storage in a high-altitude Polylepis woodland in the Peruvian Andes. *Alpine Botany*, *124*(1), 71–75. https://doi.org/10.1007/s00035-014-0126-y
Verhagen, W., Van Teeffelen, A. J. A., Baggio Compagnucci, A., Poggio, L., Gimona, A., & Verburg, P. H. (2016). Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. *Landscape Ecology*, *31*(7), 1457–1479. https://doi.org/10.1007/s10980-016-0345-2
Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., & Bradley, R. S. (2008). Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, *89*(3–4), 79–96. https://doi.org/10.1016/J.EARSCIREV.2008.04.002
Wei, H., Fan, W., Lu, N., Xu, Z., Liu, H., Chen, W., Ulgiati, S., Wang, X., & Dong, X. (2019). Integrating biophysical and sociocultural methods for identifying the relationships between ecosystem services and land use change: Insights from an Oasis area. *Sustainability (Switzerland)*, *11*(9). https://doi.org/10.3390/su11092598
Wiegers, E. S., Hijmans, R. J., Herve, D., & Fresco, L. O. (1999). Land use intensification and disintensification in the Upper Canete valley, Peru. *Human Ecology*, *27*(2), 319–339. https://doi.org/10.1023/a:1018729428781
Wulder, M. A., Coops, N. C., Roy, D. P., White, J. C., & Hermosilla, T. (2018). Land cover 2.0. In *International Journal of Remote Sensing* (Vol. 39, Issue 12, pp. 4254–4284). https://doi.org/10.1080/01431161.2018.1452075
Xu, S., Liu, Y., Wang, X., & Zhang, G. (2017). Scale effect on spatial patterns of ecosystem services and associations among them in semi-arid area: A case study in Ningxia Hui Autonomous Region, China. *Science of the Total Environment*, *598*, 297–306. https://doi.org/10.1016/j.scitotenv.2017.04.009
Yang, G., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C., Du, Y., Fan, X., Ren, Y., & Chang, J. (2015). Using

ecosystem service bundles to detect trade-offs and synergies across urban-rural complexes. *Landscape and Urban Planning*, *136*, 110–121. https://doi.org/10.1016/j.landurbplan.2014.12.006

Young, B. E., Young, K. R., & Josse, C. (2008). Vulnerability of Tropical Andean Ecosystems to Climate Change. *Climate Change and Biodiversity in the Tropical Andes*, 170–181.

Young, K. R. (2009). Andean land use and biodiversity: Humanized landscapes in a time of change. *Annals of the Missouri Botanical Garden*, *96*(3), 492–507. https://doi.org/10.3417/2008035

Young, K. R. (2014). Ecology of land cover change in glaciated tropical mountains. *Revista Peruana de Biologia*, *21*(3), 259–270. https://doi.org/10.15381/rpb.v21i3.10900

Zen, M., Candiago, S., Schirpke, U., Egarter Vigl, L., & Giupponi, C. (2019). Upscaling ecosystem service maps to administrative levels: beyond scale mismatches. *Science of the Total Environment*, *660*, 1565–1575. https://doi.org/10.1016/j.scitotenv.2019.01.087

Zheng, Z., Fu, B., Hu, H., & Sun, G. (2014). A method to identify the variable ecosystem services relationship across time: a case study on Yanhe Basin, China. *Landscape Ecology*, *29*(10), 1689–1696. https://doi.org/10.1007/s10980-014-0088-x

Zimmermann, M., Meir, P., Silman, M. R., Fedders, A., Gibbon, A., Malhi, Y., Urrego, D. H., Bush, M. B., Feeley, K. J., Garcia, K. C., Dargie, G. C., Farfan, W. R., Goetz, B. P., Johnson, W. T., Kline, K. M., Modi, A. T., Rurau, N. M. Q., Staudt, B. T., & Zamora, F. (2010). No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes. *Ecosystems*, *13*(1), 62–74. https://doi.org/10.1007/s10021-009-9300-2

Legends

Fig. 1

Study area (left) and relevant LULC units for the 25 administrative boundaries in 2000 and 2013 (right). Maps were made using ArcMap 10.3 (http://desktop.arcgis.com/en/arcmap/). Study area background from World Reference Overlay (Sources: Esri, Garmin, USGS, NPS) and World Terrain Base (Sources: Esri, USGS, NOAA). Source administrative limits: Instituto Nacional de Estadística e Informática (Peru), http://geoservidorperu.minam.gob.pe/geoservidor/download.aspx. LULC map in 2000 made from map of high-Andean ecosystems http://geoservidorperu.minam.gob.pe/geoservidor/download.aspx. LULC map in 2013 made from official flora cover map, http://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/

Fig. 2

ES matrix (A) and descriptive statistics for the sensitivity analysis (B and C). (A) The matrix illustrates the flow of regulating and provisioning ES potential supply in the moist Puna. (B) The graph displays the standard deviation for expert responses in each LULC/regulating ES pairs. (C) The ES sensitivity matrix 1 shows the expert scores plus the standard error. The ES sensitivity matrix 2 presents the expert scores minus the standard error. The cells with red outline denote a one-level class variation in the potential supply

Fig. 3

Clusters of land-change dynamics spatially distributed over the years 2000 and 2013. Star plots illustrate the land-change dynamics and the total percentage of transformed land (ΔCH) for each bundle. Each ray length is proportional to the percentage of changed land of its corresponding dynamic (rays are comparable within bundles). Dynamic types and abbreviations: agricultural expansion (D1), agricultural de-intensification (D2), deforestation (D3), urbanization (D4), afforestation (D5) and natural processes (D6)

Fig. 4

Spatial distribution of ecosystem service bundles (ESB) grouping the ES potential average trends over 2000 and 2013. Barplots show the ES potential average variation within each bundle type. Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS).

Fig. 5

Star plot and barplot describes each link between clusters of land-change dynamics and ecosystem service trends. Star plots illustrate the land-change dynamics and the total percentage of transformed land (ΔCH) occurred in each province. Each ray length is proportional to the percentage of changed land of its corresponding dynamic (rays are comparable within provinces). Barplots show the ES potential variation within each province. Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS). Dynamic types and abbreviations: agricultural expansion (D1),

agricultural de-intensification (D2), deforestation (D3), urbanization (D4), afforestation (D5) and natural processes (D6)

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Author Contributions

S.M-M. and JL.M.G. designed the study; S.M-M. developed each section of the research and wrote the manuscript. JL.M.G. read and accepted the final version.

Competing Interests

The authors declare no competing interests.

ARTICLE

ASSESSMENT METHOD AND SCALE OF OBSERVATION INFLUENCE ECOSYSTEM SERVICE BUNDLES

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Abstract: The understanding of relationships between ecosystem services and the appropriate spatial scales for their analysis and characterization represent opportunities for sustainable land management. Bundles have appeared as an integrated method to assess and visualize consistent associations among multiple ecosystem services. Most of the bundle assessments focused on a static framework at a specific spatial scale. Here, we addressed the effects of applying two cluster analyses (static and dynamic) for assessing bundles of ecosystem services across four different scales of observation (two administrative boundaries and two sizes of grids) over 13 years (from 2000 to 2013). We used the ecosystem services matrix to model and map the potential supply of seven ecosystem services in a case study system in the central high-Andean Puna of Peru. We developed a sensitivity analysis to test the robustness of the matrix. The differences between the configuration, spatial patterns, and historical trajectories of bundles were measured and compared. We focused on two hypotheses: first, bundles of ecosystem services are mainly affected by the method applied for assessing them; second, these bundles are influenced by the scale of observation over time. For the first hypothesis, the results suggested that the selection of a method for assessing bundles have inferences on the interactions with land-use change. The diverse implications to management on ecosystem services support that static and dynamic assessments can be complementary to obtain better contributions for decision-making. For the second hypothesis, our study showed that municipality and grid-scales kept similar sensitivity in capturing the aspects of ecosystem service bundles. Then, in favorable research conditions, we recommend the combination of a municipal and a fine-grid scale to assure robustness and successfully land-use planning processes.

Keywords: ecosystem service bundles; cluster analysis; scale effects; spatiotemporal analysis; mountain agro-ecosystem; capacity matrix; GIS; landscape planning; landscape management

1. Introduction

The ecosystem services (hereafter ES) concept—the benefits obtained from nature for human well-being [1]—has become an integrated framework in sustainability science [2]. The ES framework facilitates ecosystem conservation opportunities [3] and affords innovative and valuable data to help decision-making [4]. In that sense, ES research is a significant and rising field of research [3], gathering studies around the world that are largely focused on the assessment and the management of the state of ES [3,5]. Relationships between ES are an issue that has received increasing interest in the literature [6–10]. These review studies addressed the importance of the analysis of relationships between ES.

ES relationships vary over time [11–14] and depending on the scale of observation. For example, a situation of mutual enhancement among a pair of ES at the county level could become in an increase in one service at the expense of the other at grid scale [15]; also, a set of ES characterized by a multifunctional pattern of supply at municipality level can derive in a set of

ES dominated by the provision of few services at the patch scale [16]. These relationships, namely synergies and trade-offs [17,18] and bundles [19], can also differ on the method for assessing them. For example, the correlation analysis between two ES for a given time can detect a trade-off, while the same analysis between the differences in ES supply at two times detect a synergy [20].

However, most of the assessments focused on a simple (static) method for estimating ES on a specific spatial scale [21], and few studies integrated historical analysis (e.g., in [11,12,22,23]). Thus, only a limited number of studies identified the effects of different spatial scales on ES (e.g., in [16,24–28]), but using a snapshot approach (ES assessment at a single point in time). Thus, improvement of the characterization of spatiotemporal co-occurrences of ES, applying different assessment methods at different scales of observation, can contribute to reinforcing efficient management strategies that seek to achieve win–win solutions [9].

Among the common methods for assessing ES relationships, there is correlation analysis, and cluster analysis [10,29]. Correlation analysis is mostly applied to measure the degree of statistical dependency between a pair of ES for a given time in order to classify their relationship as trade-off or synergy [6,30]. Cluster analysis is one of the main statistical methods utilized for the estimation of bundles of ES for a given time [8,31]. Bundles have appeared as an integrated method to assess and visualize consistent associations among multiple ES derived from the different land use and land cover types [19]. Different authors explored how the ES bundle concept contributes to including ES models into land-use planning [32,33], to clarify the impacts of land-change dynamics on ES [12], to identify priority areas for ES management [34], to distinguish social preferences toward ES [35] or to investigate ES bundles for analyzing trade-offs [19,36–38]. Despite these increasing efforts, there are still two main current methodological limitations. One related to the deficiency of standardized applicable assessment methods of ES [21,39], and other to the understanding of how the relationships between services changes at multiple time steps, and which might be the appropriate spatial scales in empirical or modeling ES research [40,41]. The different methods applied for the assessment of relationships between ES can lead to different interpretations [6,20,42,43]. Added to this, the use of a single scale of observation on ES assessments can lead to the avoidance of relationships between ES and ignore differences in spatial patterns between them when changing analysis scales [15,16,28].

In this study, we aim at examining the differences in applying two frameworks (static and dynamic) for the assessment of bundles of ES at four scales of observation over time, to provide new insights for better management of ES. To achieve these objectives, we addressed two hypotheses: first, bundles of ES are mainly affected by the method applied for assessing them; second, these bundles are influenced by the scale of observation over time. We develop the research in a case study system in the central high-Andean Puna of Peru [12,44]—this section of the moist Puna region shows a distinctive socio-ecological significance. The moist Puna (Peru and Bolivia) has been occupied, and its resources profited during several millennia by Andean civilizations [45,46]. This mountain environment, where its main social ecosystems consist of natural grassland, shrubland, and agricultural areas, can provide multiple ES [47].

We performed the analyses using the ES matrix. It is a successful method, appropriated worldwide [48,49]. It consists of an evaluation of ES using land use/land cover maps and expert estimation that is useful for spatial comparisons between regions [50]. The expert knowledge serves as a surrogate of empirical observations in many scientific studies [51]. Roche and Campagne [52] have proved that expert knowledge through the matrix approach can be as valid as the use of empirical data or biophysical indicators for ecosystem service assessment. Moreover, the matrix provides a high performance to integrate all types of information, and when the source data are scarce, this method can be the best accessible alternative for ES estimations [53], helping cross-study comparisons and decision-makers to solve the necessity of more ES appraisals for land management.

In our work, we studied the effects of applying two cluster analyses for assessing bundles of ES over time (years 2000, 2009, and 2013). We computed one (static) analysis with ES values and one (dynamic) with the amounts of changes in ES values at two times (ΔES, for short). We performed the assessments across four scales of observation: two administrative levels (provincial and municipal) and two grid resolutions (3 × 3 km and 0.25 × 0.25 km). To determine the differences between the results of each method, we measured and compared the configuration, spatial patterns, and historical trajectories of ES bundles. Additionally, a sensitivity analysis that simulated a scenario with changes in the scores of ES potential supply over time tested the inconsistencies of the ES matrix on the findings.

2. Materials and Methods

2.1. Study Site

The selected area is a section (12 provinces, 27,612 km²) of a larger study site (24 provinces, 64,025 km²) of previous studies [12,44] in the central high-Andean moist Puna (administrative departments of Junin, Huancavelica, and Ayacucho) (Figure 1). During the study period, these chosen provinces are characterized by high land-use change intensity [44], mainly due to farming expansion, agricultural de-intensification and deforestation [12]. Additionally, this study site has a high population density in the moist Puna, about 44 inhab./km² (2013), with the strongest urban development in the metropolitan areas of the two major cities, Huancayo and Ayacucho [54].

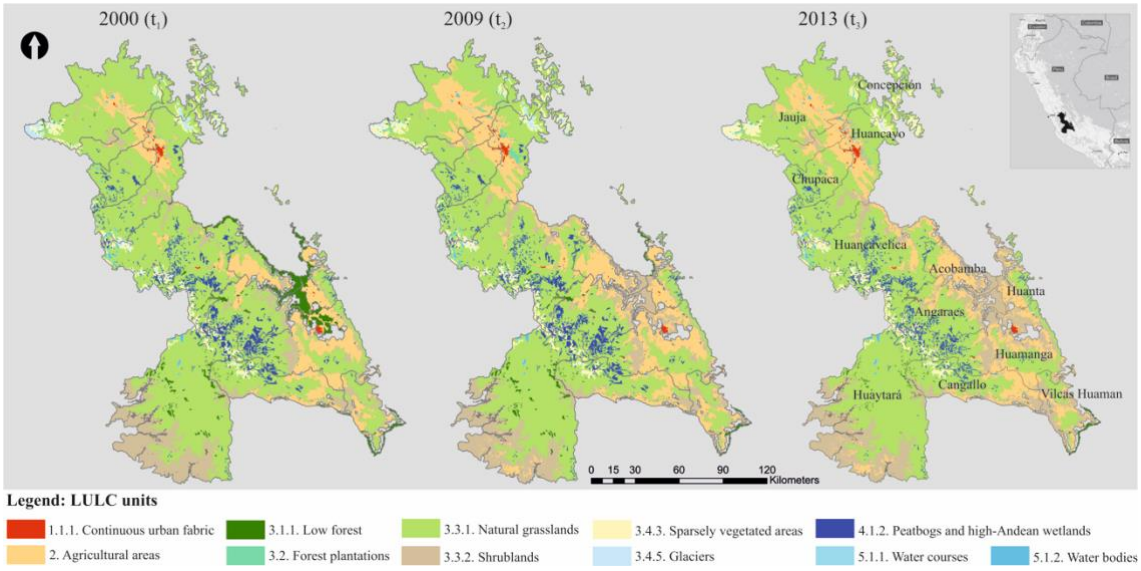

Figure 1. The 12 provinces in the central high-Andean moist Puna over time. The maps display the land use/land cover (LULC) units for each time step from 2000 to 2013. The map at the right-top shows the location of the study site in Peru.

This landscape is dominated by an expansion of livestock breeding in the upper lands and an increase in farming in the fertile lowlands. This is typical of many mountain agroecosystems across the world. Most of this territory is embedded within the Mantaro river basin, including ecosystem services associated with agricultural practices (crops and livestock provision, regulation of soil erosion and maintenance of soil quality), hydrological cycle (water purification and water flow regulation) and climate regulation. However, the main land use/land cover in the study area consists of natural grasslands (59%), shrublands (16%), and agricultural lands (15%) by 2013 (Table S1, Supplementary Materials). The diverse combination of them formed three groups of landscapes. A group of provinces (Acobamba, Huamanga, Huanta, and Vilcas Huaman) show a uniform distribution of the main land use/land cover (hereafter LULC) units

(31%, 34%, and 31%, respectively). The second pattern, described by two provinces (Jauja and Chupaca), displays a territory mainly dominated by two LULC units (72% of natural grassland and 19% of farming areas). The third group of provinces (Angaraes, Cangallo, Concepcion, Huancavelica, Huancayo, and Huaytara) discloses a landscape characterized by low farming development (14%), the highest high-Andean wetland coverage (3%) and high pasture extent (63%).

2.2. Land Use/Land Cover Data Sources

The study area is covered by 11 LULC types (Figure 1). These categories, included in the Peruvian standardized nomenclature of the Corine Land Cover (CLC), were derived from three-time data sources: the map of high-Andean ecosystems in 2000 [45], the official flora cover map from 2009 [55], and the official flora cover map from 2013 [56]. According to the official sources, the maps were submitted to a verification and field survey procedure for improving the accuracy of the land use/land cover classification. However, the different geographical scales made necessary a generalization of the land use/land cover classes. Table S2 (see Supplementary Materials) shows the harmonization of the three-time step features to obtain a common legend of eleven LULC units. Moreover, the description of satellite images, mapping scale, minimum mapping area, and type of data of the three source maps are specified in Table S3 (see Supplementary Materials).

2.3. Ecosystem Services Potential Supply

The study is based on the capacity matrix that was done specifically for assessing the ES in the study area, developed by Madrigal-Martínez and Miralles i García [12] (subsequently referred to as the High-Andean Study). The assessment obtained the potential supply of 7 site-specific ES identified by the Common International Classification of Ecosystem Services [57]—two regulating services related to mediation of flows (regulation of soil erosion and water flow regulation); one ES related to filtration, sequestration, storage or accumulation by ecosystems (water purification); two services linked to the maintenance of physical, chemical, biological conditions (soil quality and global climate regulation) and, finally, two provisioning services related to nutrition (crops and reared animals).

To develop the ES matrix, the High-Andean Study consulted 43 experts to rank the ES potential supply associated with a specific LULC on a relative spatial scale, ranging from 0 (no relevant ES potential supply) up to 5 (very high ES potential supply). The experts were carefully selected to increase confidence according to their specific skills on ES and the moist Puna ecosystems. Additionally, the survey was thoroughly described individually, and they scored only the LULC/ES pairs that were sure in their judgments. Each response was collected and deprived of outliers using the interquartile range method. Then, a final score was computed using the mean. Furthermore, the potential supply of the LULC in provisioning services was achieved from official model results included in land planning instruments of the administrative departments under study. Table S4 (see Supplementary Materials) provides the maximum capacity of the eleven LULC categories to supply the seven ES. The ecosystem services were set as constant values assuming that land units are in good condition during the study period.

2.4. Scaling Method

The ES and ΔES maps were derived from the matrix model and upscaled to four spatial scales: two administrative divisions (provincial and municipal) and two grids (coarse and fine). The four spatial scales were selected for their particular importance in spatial planning and ecosystem services mapping. The provincial level (~10^3 km^2) has a central role in the Peruvian planning system binding national and departmental directives with local interventions (Organic Law of Municipalities No. 27,972). The municipal level (~10^2 km^2) is where land-use management

in urban areas and the countryside are made. Coarse-grid resolution (9 km²) was chosen because it explores patterns of ecosystem services and approximates a locality. A fine-grid (0.25 km²) was included because it is where individual land-use management and land-cover changes occur. This spatial scale was decided as the finest because the study maps are based on a geographical scale of 1:100 000, and following the Corine Land Cover approach and the official flora cover map from 2009 [55], this spatial resolution corresponds to the minimum mapping area. Both grid resolutions are important for planning green infrastructure to support human well-being.

The administrative areas were calculated using boundaries from the Peruvian National Institute of Informatics and Statistics. The 12 provincial units range from 750 to 6075 km² (with an average of 2301 km²), whereas the 175 municipality units vary from 5 to 2176 km² (with an average of 158 km²). On the other hand, the coarse-grid (3 × 3 km) and the fine-grid (0.5 × 0.5 km) resolutions were both generated using the Fishnet tool and the Geoprocessing tool in ArcGIS 10.3 [58]. The coarse-grid comprises 3019 cell units, while the fine-grid has 110,343 spatial units. The cells with at least 95% of their area within the boundaries of the study area were included.

After this, each of the four maps of spatial units was separately intersected with every LULC map of each year (2000, 2009, and 2013), obtaining 12 maps. Next, the ES matrix was applied on these 12 maps deriving 84 maps of ES potential supply. These potential supply maps were aggregated to their corresponding spatial resolution by using Equation (1):

$$ES_{ns} = \frac{\sum_{i=1}^{s} (ES_i \times A_i)}{S} \quad (1)$$

where ES_{ns} is the potential supply of a given spatial unit s for a given ecosystem service n, ES_i is the score assigned to a given LULC unit i, and A_i is the area of that given LULC unit i within the given spatial unit n. S is the total area of the given spatial unit. Figure S5 (see Supplementary Materials) provides a graphical sample of the scaling method.

Lastly, to obtain the upscaled ΔES values over the two periods, from 2000 (t_1) to 2009 (t_2) and 2009 (t_2) to 2013 (t_3), Equation (2) was used:

$$\Delta ES_{ns} = ES_{ns}(t_{k+1}) - ES_{ns}(t_k) \quad (2)$$

where ΔES_{ns} is the potential supply of a given spatial unit s for a given ecosystem service n of the final year t_{k+1} minus the potential supply of that given spatial unit s for the given ecosystem service n of the initial year t_k.

2.5. Cluster Analyses

Cluster analysis was selected for assessing bundles of ES at each scale of observation. This method was computed two times: (1) using the ES values at the three dates (2000, 2009, 2013), and (2) using the ΔES values for the two periods (2000–2009, 2009–2013). Then, to identify differences, the results of each assessment were compared.

The best number of clusters was determined using the "NbClust" R package [59] configured with the combination of "euclidean" distance measure, "kmeans" method, "alllong" index, and a significance value of 0.1 for Beale's index. This package was run (n = 4) with ES and ΔES values at the provincial and municipal levels. The majority of indices proposed three clusters as the best number in all datasets. Bundle types were identified applying a k-means cluster analysis run with 10,000 iterations in R [60]. The k-means cluster analysis grouped the values in three specific combinations of ES based on their characteristics. For later comparisons, the bundles were named: bundle type 1, bundle type 2, and bundle type 3. Each bundle type was drawn using Excel 2015. The different aspects of bundles were analyzed with standard metrics (Table 1). Then, the results were compared to identify differences (effects) that can establish trends. To estimate the configuration metrics, Excel 2015 was used. The spatial patterns and historical trajectories were computed using ArcGIS 10.3 [58].

Table 1. Metrics (and their description) used for the achievement of the aspects of bundles.

Aspect	Metric	Description
Configuration	True Diversity (Order 2) (^2D)	The diversity of a set of ES provided in a given bundle type is calculated as the effective number of ecosystem services based on Hill numbers [61,62]. For the "dynamic bundles", we used the absolute value of each amount of change in ES specified by a given bundle. This metric was included because it affords a stable, clearly understood, and sensitive overall similarity measure supporting cross-study assessments [11,62].
	Abundance (N)	The sum of the absolute value of each ES (or ΔES) specified by a given bundle type. The sum represents an overall level of the provisioning of services (or of the change in services). High absolute values thus indicate zones with a comparatively high supply of (or change in) multiple services, while low values indicate the opposite. This metric was included in the bundle analysis because policies are intended to protect the overall level of ES provision rather than, or in addition, to the provision of individual services.
Spatial patterns	Percentage of land	The proportional abundance of a given bundle type in a given year or a given period across the study area. It is a landscape metric that acts as a proxy for change, thus allowing for the interpretation of spatial patterns over time and space. This metric measured the results of both cluster analyses.
Historical trajectories	Percentage of land change	The proportion of land changing from one bundle in a year or period *t* to another in a year or period *t+1* on the same spatial scale. This metric measured the results of both cluster analyses.

2.6. Sensitivity Analysis

A sensitivity analysis of the ES matrix was applied to test the robustness of the methodological approach. The analysis consisted of the development of a sensitivity scenario based on a four steps method adapted from the five common stages of a scenario development [63]. In the first step, the aim of the sensitivity analysis was defined—to test how changes in the scores of ES potential supply of the High-Andean Study matrix affects the results over time. In the second step, two key drivers and their trends that affected (positively or negatively) the potential supply of services were identified from interviews with five experts: climate change and technological improvement of agriculture and forestry.

In stage three, the scenario assumptions were deducted using the trends of the key drivers. These trends were simulated as a rate of positive/negative change (+/− 0.1 per year) on the ES values of the LULC units. Climate change had negative consequences on regulating services supplied by the following ecosystems: natural grasslands, shrublands, forests, glaciers, and high-Andean wetlands. On the contrary, well-managed farming enhanced regulating (erosion, water flow, and soil quality) and provisioning services of agricultural areas and reduced the pollution of rivers and lakes, recovering their functions of purifying water and flow control. Likewise, the technological improvement of forest plantations increased, regulating services (soil quality, control of soil erosion, water flow, and global climate regulation). The scores of ES for continuous urban fabric and sparsely vegetated areas stayed unaffected.

In stage four, with the simulated scores of ES, two new model matrices for 2009 and 2013 were generated (see Tables S6 and S7 in the accompanying Supplementary Materials), whereas, for 2000, that created by the High-Andean Study was used. From these matrices, the ES maps at the four spatial scales were derived running the scaling method defined in Section 2.4. Finally, the assessments of relationships between ES were performed following Section 2.5.

3. Results

3.1. Static Cluster Analysis

The results of the two metrics used to evaluate the effects of the four spatial scales on the configuration of bundles showed similarities and disparities (Figure 2A). Regarding similarities, all the bundles provided an effective number of ES that ranged from 6.51 to 6.87. Concerning dissimilarities, most of the bundle types indicated disproportions among the abundance of ES. However, it showed a trend towards being higher for large spatial scales. Additionally, there was a trend of increasing of ES abundance from bundle type 1 to type 3 at each spatial resolution, but it had more similarities when the spatial scale increased. In that way, the provincial level was defined by the slight variation of ES values of the three bundle types. However, at the municipal level, type 3 was a multifunctional bundle, type 2 was a multifunctional agricultural bundle, and type 1 corresponded to an agriculture bundle. The coarse-grid scale mainly differed from the municipal in the bundle type 1 (agriculture and sparsely vegetated areas). However, at the fine-grid, the ES bundling showed a multifunctional bundle (type 3), an agriculture bundle (type 2), and an urban and sparsely vegetated area bundle (type 1).

The sensitivity analysis showed similarities between the effective number of ES provided by all the bundles, whereas the highest differences were detected among the abundance of bundles (Figure 2B). The diversity and the abundance of ES provided in bundles type 3 and type 2 was similar at the four scales of observation, whereas in type 1, differed. Thus, type 3 was a bundle with the highest values of regulating services, and type 2 was a bundle with the highest values in crop and livestock services. However, type 1 at the provincial level kept similarities with type 2, whereas at the municipal and grid scales had the lowest values of ES defined by urban and sparsely vegetated areas.

The spatial distribution of bundles obtained from ES values showed higher similarities among the three smaller spatial scales (Figure 3A). Thus, bundle type 3 dominated the territory (percentage of land >63%) over the three years. Nevertheless, the agricultural bundle had higher correspondences between grid-scales. At the provincial level, the three types of bundles were more evenly distributed (Figure 3A). The sensitivity analysis showed that the similarities between the spatial distribution of bundles followed a trend towards being higher for small spatial scales (Figure 3B). Then, at the municipal level and the two grid-scales, bundles kept fair spatial consistency across time, especially for types 2 and 3. On the contrary, at the provincial level, the territory was defined by a bundle type each year.

The analysis of historical trajectories showed that the bundle provided by any given land changed through time at each spatial scale but followed a decreasing trend from large to small (Table S8, Supplementary Materials). During the total study period, at the provincial level, 68% followed any trajectory of change, whereas this change was 30% at the municipal level. In the same way, the coarse-grid and fine-grid showed inferior variations of 24% and 14%, respectively. Furthermore, there was a second trend towards a higher number of transitions for fine spatial scales. These two trends were confirmed by the sensitivity analysis (Table S9, Supplementary Materials).

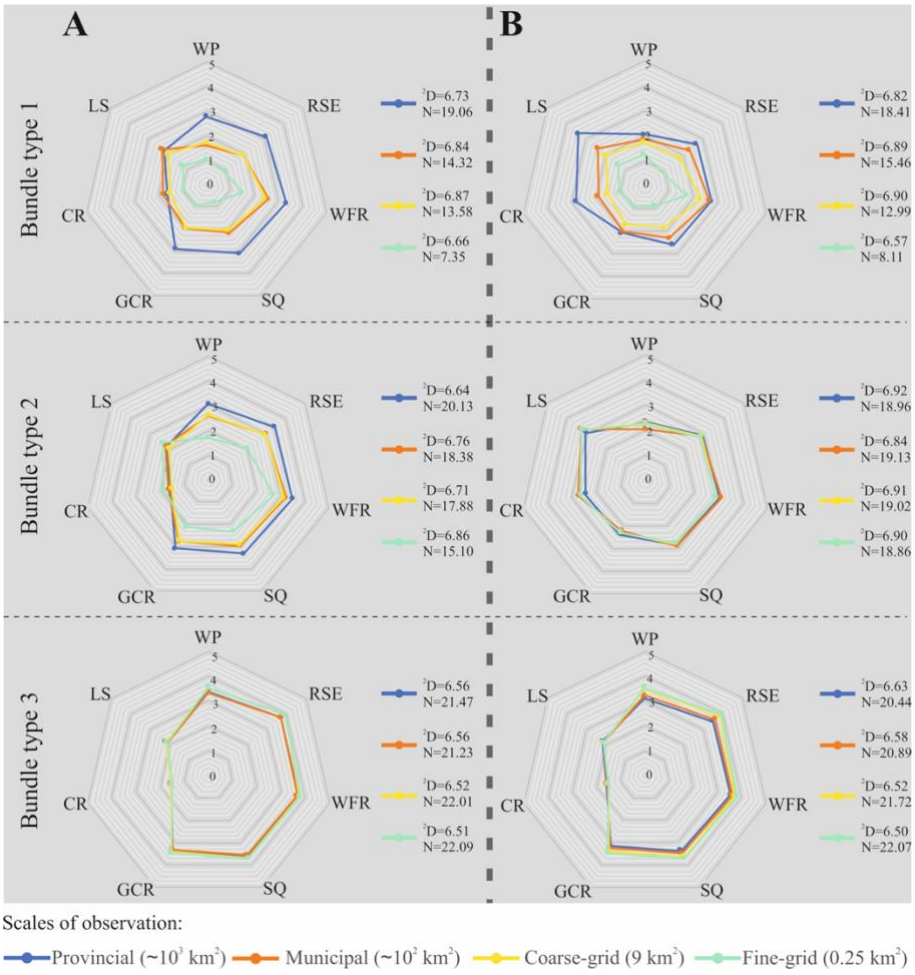

Figure 2. Configuration of bundles and metrics derived from ES values (**A**) and the sensitivity analysis (**B**) at the four spatial scales. Spider charts illustrate the abundance of ES potential supplied by each bundle. Each axe length is proportional to the relative abundances of the other ES within each bundle (axes are comparable within bundles). Metrics and abbreviations: true diversity (^2D), and abundance (N). Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS).

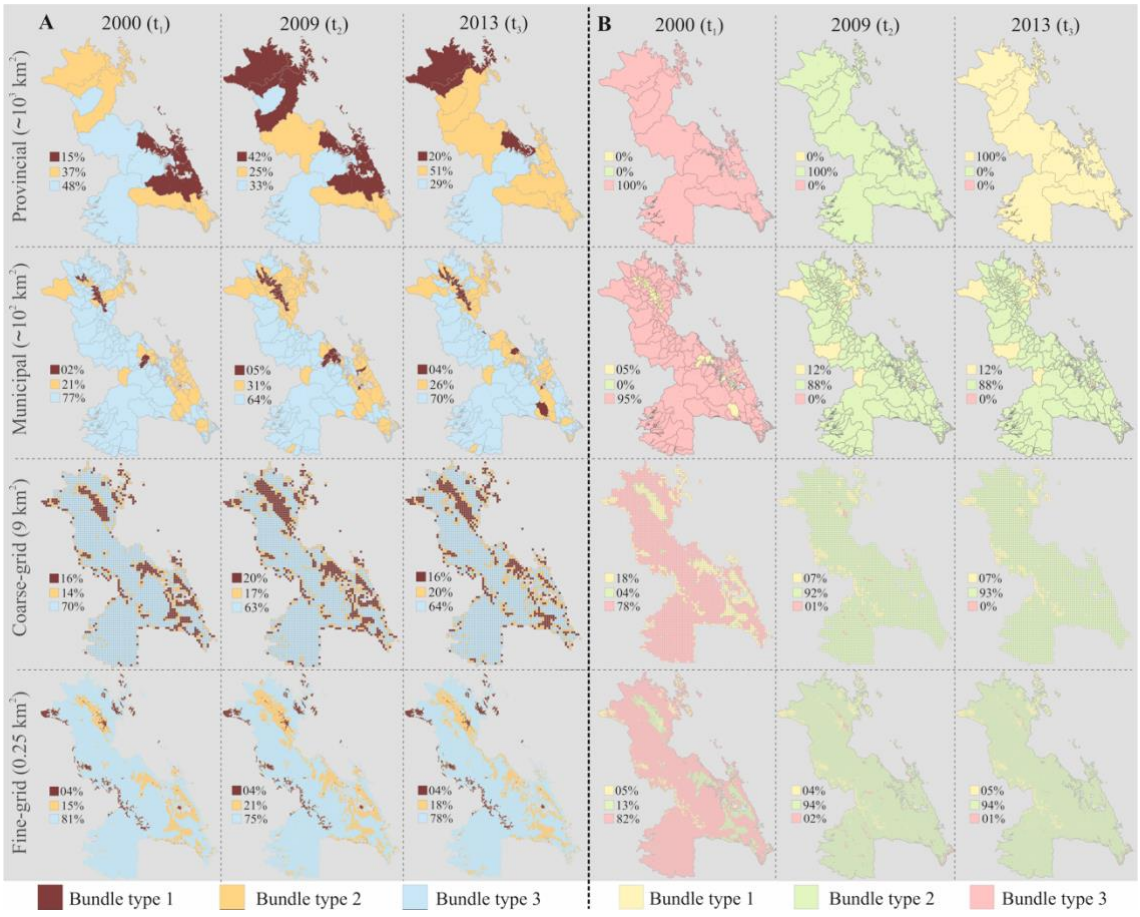

Figure 3. Spatial distribution of bundles resulting from ES values (**A**) and the sensitivity analysis (**B**) across the four spatial scales over the three years. Maps show the spatial distribution and proportion of land of each bundle over time and across each spatial scale.

3.2. Dynamic Cluster Analysis

The analysis of the configuration of bundles at the four spatial scales presented similar measures of the effective number of ES changes (that ranged from 5.30 to 6.07), but differences in most of the N values (Figure 4A). Only bundle type 2 did not manifest these dissimilarities, since describing a territory without land-use change at the four spatial resolutions, remaining with similar and lowest N (almost 0). On the contrary, the N values specified by bundles type 1 and type 3 decreased when the spatial scale increased. In this regard, bundle type 1 revealed an increasing pattern from larger to smaller spatial scales, that detected the reduction in regulating services, and the increase in provisioning ES. However, bundle type 3 specified a trend of increase in provisioning services and a decrease in regulating.

For the sensitivity analysis, Figure 4B shows the similarities and the differences between the configuration of bundles across the four spatial scales. Similarities of the ^{2}D metric are found for types 1 and 3, whereas type 2 showed higher differences across the four spatial scales. On the other hand, the N metric showed that for each bundle type, grid-scales had higher similarities between them and the municipality level. Furthermore, bundles type 1 and type 3 showed a consistent configuration of positive values of provisioning services and negative of regulating, whereas type 2 differed at the provincial level in the regulating services. Thus, bundles showed higher similarities among the three smaller spatial scales.

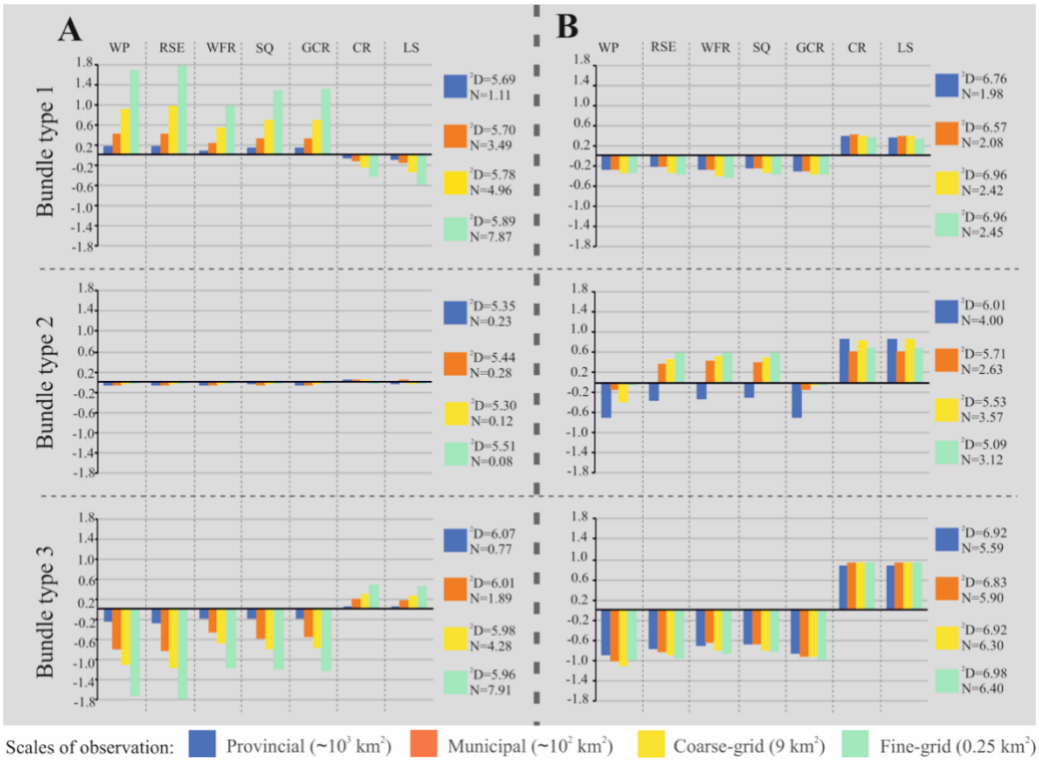

Figure 4. Configuration of bundles and metrics derived from ΔES values (**A**) and the sensitivity analysis (**B**) at the four spatial scales. Bar plots show the amount of change in ES values at two times within each bundle type. Each bar length is proportional to the relative abundances of the other ΔES values within each bundle (bars are comparable within bundles). Metrics and abbreviations: true diversity (^2D), and abundance (N). Ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ), global climate regulation (GCR), crops (CR) and livestock (LS).

The spatial distribution of bundles across the two smaller spatial scales displayed a consistent pattern that began to be less evident at the provincial level (Figure 5A). In that sense, at the municipal level and on the two grid-scales, the territory seemed dominated by bundle type 2 (percentage of land >84%), whereas this percentage high declined at the provincial level. Likewise, the sensitivity analysis indicated fair robustness between municipal and grid-scales (Figure 5B). However, there were minor areas with changes in ES supply only detected at grid resolutions.

Historical trajectories of bundles achieved with ΔES values showed that the land that changed from one to another differed among spatial scales but was higher (52%) at the provincial level than at smaller levels (municipal: 24%; coarse-grid: 16%; fine-grid: 13%) (Table S10, Supplementary Materials). These transitions uncovered four main trajectories at all the spatial scales, and two more only found at the grid scales. Likewise, the sensitivity analysis showed that the proportion of land changing from one bundle to another was higher at the provincial level, and the number of trajectories was higher as the spatial scale decreased (Table S11, Supplementary Materials).

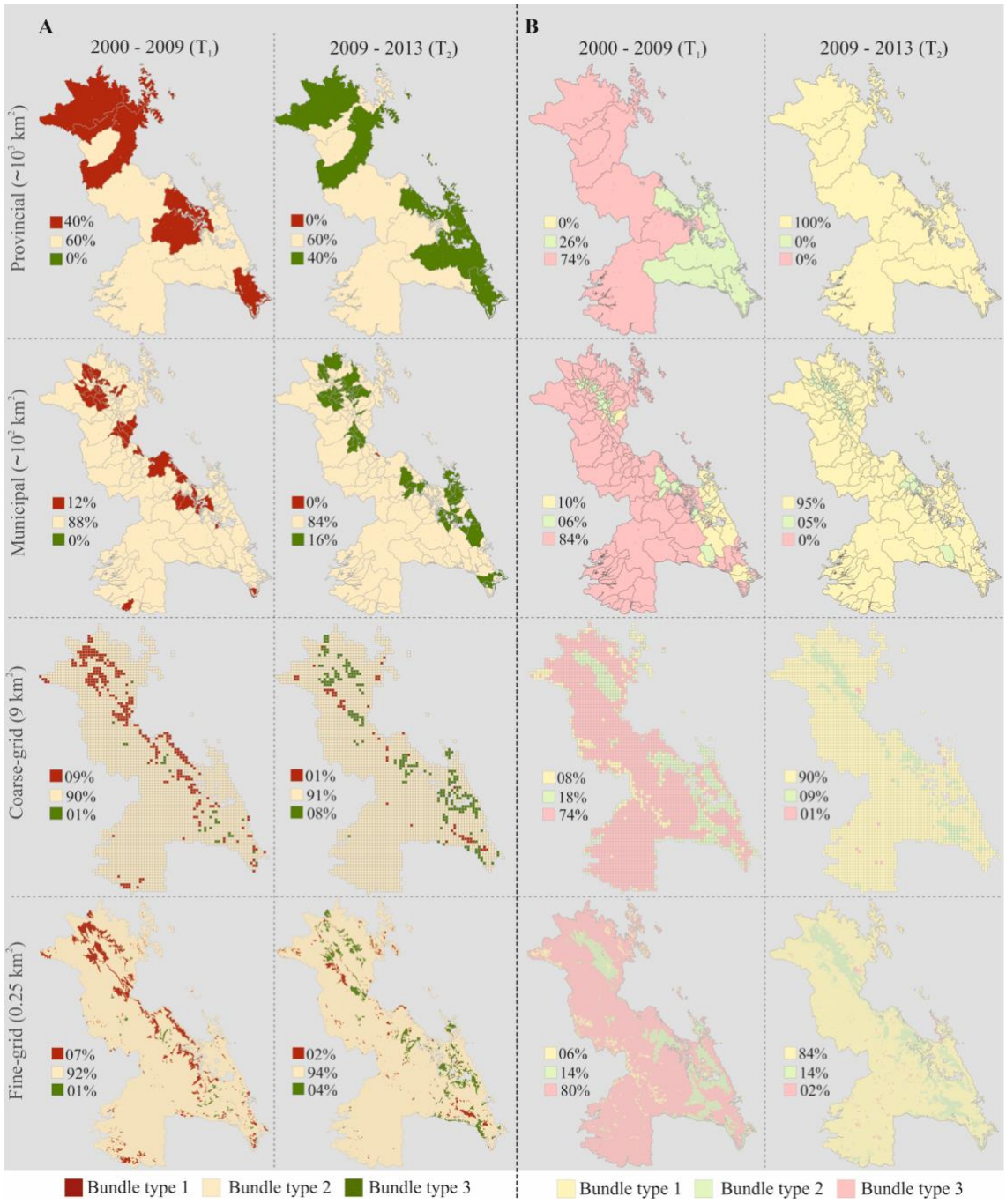

Figure 5. Spatial distribution of bundles resulting from ΔES values (**A**) and the sensitivity analysis (**B**) across the four spatial scales at each period. Maps show the spatial distribution and proportion of land of each bundle over the two-time periods and across each spatial scale.

4. Discussion

In our study, the ES matrix contributes to the assessment of relationships between ES, applying two different methods (static and dynamic) across four scales of observation over time. At the spatial scale level, it revealed several findings consistent with those found by comparable biophysical assessment [16]. We analyzed the differences between each assessment method by comparing the results of standard metrics at each spatial scale over time. Subsequently, we discuss the main findings of the study validated by the sensitivity analysis (Table 2) and organized as scale and assessment method effects that might have implications on ES management.

Table 2. Scale and assessment method effects on bundles of ecosystem services.

Assessment Method Effect	Spatial Scale Effect
• Configuration: disagreement in the direction of the relationships between multiple ES. • Spatial patterns: static cluster analysis captured only a snapshot of ES bundles at different years, whereas cluster analysis with ΔES values displayed dynamics of ES bundles.	• Configuration: static cluster analysis displayed a trend towards more similarities among bundle types for large spatial scales, whereas dynamic cluster analysis showed a similar trend of positive and negative change in the ES supply at the three smaller spatial scales. • Spatial patterns: static cluster analysis suggested higher similarities between bundles at the municipal level and the two grid-scales, whereas dynamic cluster analysis showed some consistency across spatial scales. • Historical trajectories: both cluster analyses detected: (1) a trend towards a high percentage of land change for large spatial scales, and (2) a trend towards a high number of trajectories for fine spatial scales.

4.1. Effects of Different Cluster Assessments on Bundles of ES

Depending on the cluster assessment, we found relationships between multiple ES that shifted in different ways. This finding agrees with previous work that also confirmed that the chosen method influences the result [6,20,42]. In that sense, in our study, "static bundles" suggested a positive spatial co-occurrence among the seven ES. On the contrary, "dynamic bundles" proposed a negative relationship between provisioning and regulating services. The synergy detected with the static assessment shows an opportunity to enhance multiple ES simultaneously. However, it missed the trade-off between regulating and provisioning services, and it could represent an unexpected loss of success for ES management. In fact, it implicates missing opportunities for win–win solutions that involve investments in conservation, restoration, and sustainable ecosystem use [64].

The spatial distribution of bundles captured by each cluster assessment showed differences. Thus, ES values displayed a landscape characterized by bundles with a specific diversity and abundance of ecosystem services supply at each time-step. On the other hand, ΔES values addressed the dynamics of ES bundles over the two time-periods. This last interpretation may facilitate the understanding of the instabilities that produce the temporal dynamics on ecosystems since trends expose whether there has been a change and the specified event that caused it [65]. This finding concerning "dynamic bundles" is consistent with previous research for the knowledge of land-changes dynamics [12].

4.2. Effects of Different Scales of Observation on Bundles of ES

The static assessment of bundles suggested that the configuration followed a trend towards more similarities at large spatial scales (Figure 2). This effect may explain that large spatial units follow a multifunctional landscape allowing relationships between ES to concur in synergy. It is understandable because the impacts of management actions at a fine-scale may be insignificant at a larger spatial scale if the land-use type affected is scarce, which is related to the capacity to capture local heterogeneity. Thus, the relationships between ES are conditioned by the geographical size of any single land-use change in the spatial unit. Consequently, at the grid scales, bundle types were more specialized according to one LULC unit (this was evident at the fine-grid scale). However, the provincial level provided a comparative abundance of ES because

they were characterized by a similar combination of land-units. This similarity indicates comparable levels of land-use diversity that produces akin multifunctionality at large spatial units. Although multifunctionality is location related [66], this effect is observed in previous work of ES bundles across different administrative levels [16,24]. For instance, this generalization of the configuration can be inconvenient when we need to identify areas of highest/lowest supply of ES (hotspots/coldspots) for spatial prioritization or designing green infrastructure. For, as has been observed in our study site, the bundles of small size only persist across grid-scales. It implies a loss of bundle diversity when we upscale, which agrees with Zen et al. [67]. Then, large scales (dramatically at the provincial level) may fail to observe determinant factors and their influence on the sustainability of the ecosystems and their services. It reinforces the assumption that the increase in the spatial scale of observation brings a homogenization of the landscape [68], and only the mainland changes are significant [12].

At the three smaller spatial scales, bundles showed a similar configuration of positive and negative change in ES supply (Figure 4B), reflecting higher accuracy with the rate of change established by the different drivers (climate change, and technological improvement of agriculture and forestry). Needless to say, these bundles offer a basic view of the dynamic of ES that may help in planning win–win solutions. However, this basic picture depends on the size of the spatial unit, since it determines the intensity of drivers of change. In our study, as large as the spatial scale was, the land-use change impacts were more buffered. Although the provincial bundles detailed many similarities with the smaller scales of observation, the contrasts involve caution when using this spatial scale for the management of ecosystem services.

Static cluster analysis suggested high similarities between the spatial distribution of bundles at the municipal level and the two grid-scales. Consequently, it manifested fair robustness across the three smaller spatial scales, which differed with Raudsepp-Hearne and Peterson [16]. It may be related to the Andean study area, which is a landscape with ecosystem services more evenly distributed, and some amount of each ES facilitating multifunctionality can be found at the municipality level. Thus, the variation of bundling across a territory depends on the spatial heterogeneity of services since spatial homogeneity uncovers the same type of bundle across spatial scales. This diversity of findings recommends that researchers and decision-makers should be aware of the size and the heterogeneity of the spatial units to improve the aims of ES analyses [69]. Even though many times, there are limitations related to data scarcity or availability, which impede the research from being conducted optimally. We agree with previous research that considering at least two spatial scales should assure robustness [70,71], but we suggest a fine-grid scale and the municipality level. A fine-scale is important to show specific spots at local level that give a better panorama for well-informed planning decisions, whereas, at the municipality level is where political decisions are made and socioeconomic data are available. However, it is worth emphasizing that our study shows sufficient consistency between the municipal scale and the grid-scales.

The spatial distribution of bundles resulting from ΔES values revealed some consistency across spatial scales. However, bundling generalization was more evident as the scale of observation increased. This effect produces homogeneity at broad resolutions that can lead to shape a territory with similar land-use change intensity and overlooking fine-grained information needed for spatial conservation planning [72]. In our study site, at the provincial level, that generalization obscures changes in ecosystem services at lower levels that may be of importance for planning and management solutions. However, Madrigal-Martínez and Miralles i García [12] showed that, in research conditions of data scarcity, it is possible to address knowledge about land-change dynamics affecting ES that may help for policy and planning purposes at the provincial level.

For historical trajectories of bundles, both cluster analyses indicated that the area providing any given bundle changes higher at broad spatial scales over time. It implies that objects (land-units) within a large spatial unit are strongly associated, and a substantial change in one of them

affects the total, whereas minor and static zones are overlooked. In our study area, this was more evident at the provincial level, in which the variation in ES supply of a given province was due to changes only in a few land-units. It is a consequence of upscaling that has direct impacts on the intensity of land-use change affecting ES. Low intense land-use change is not significant at broad scales [12]. In that sense, only at the grid-scales minor land-use changes that configured small size bundles were detected. This effect was detected in both cluster analyses and showed a trend towards a high number of trajectories for fine spatial scales. For example, we observe that bundles characterized by an increase in regulating services at grid-scales disappear at large (municipal and provincial). It reveals that changes at larger spatial scales have a buffer effect, whereas, at the fine-scales, bundles are more sensitive to temporal changes shaped by the direct local-scale drivers. This finding supports the assumption that knowledge of local contexts of ES is policy-relevant since their changes in values and demand are finer observable over time [73,74]. Therefore, the assessment of the spatial extension under the influence of drivers could help with the understanding of the stability of ES provision, endorsing robustness for the development of sustainable management and conservation strategies.

4.3. Methodological Limitations

In this study, the analyses presented should be understood as using the best existing data of an acceptable quality to admit a robust demonstration. Even so, the method (ES matrix) brings potential limitations to the study, and technical and thematic uncertainties [75]. In that sense, we highlight that the capacity matrix simplifies landscape functionality producing uncertainties in the quantification of ES (e.g., regulating services). It is due to this that some ES are not only dependent on the presence of certain land use/land cover types but also their spatial configuration. Moreover, management actions on each land-use may affect ES flow differently (specially in provisioning services), and this effect could be measured vaguely for the matrix. Another limitation lies in that the reduced and diverse data sources of land use/land cover classes made a generalization of the landscape necessary, which could influence the bundles that emerge at larger spatial scales. In fact, a more precise number of land use/land cover classes could result in the reconfiguration of bundles [69]. Additionally, in ES matrix models, the multifunctionality is strongly dependent on the number of services provided by the different land use/land cover types [76]. On the other hand, when data at a fine-scale were summarized at the administrative levels (aggregation effect), they could cause a loss of information [77]. Finally, the data source (the map of high-Andean ecosystems) has a vague delimitation for two land units (agricultural areas and forest plantation), comprehending them in only one land-use category (Areas modified by human action). However, we considered this limitation of minor importance because this aspect was clarified using the land-use types from the two official flora cover maps.

5. Conclusions

We developed a study that addressed the effects of different cluster methods for assessing bundles of ES across different scales of observation over time, using an example in the high-Andean moist Puna. We aimed to detect the differences in applying two cluster analyses—for ES values and ΔES values—and the effects of different scales of observation—two administrative levels and two grid resolutions—on ES bundles over time. To address these objectives, we investigated two hypotheses: (1) bundles of ES differ on the method applied for assessing them; (2) these bundles are affected by the scale of observation. Our analysis uncovered consistent differences suggesting that the selection of a method for assessing bundles of ES might define the results, and the scale of observation influenced them.

"Static" bundles suggested synergies between provisioning and regulating services, whereas "dynamic" indicated negative relationships. Then, the assumption of a general pattern of trade-offs between these groups of services needs to be analyzed in detail [27,42]. The diverse interpretations found in our study suggest that both assessment methods have implications for

management of ES, and both can be complementary to obtain better contributions for decision-making. However, if research objectives are focused on the understanding of the instabilities that produce the temporal dynamics on ecosystems, we recommend the assessment of "dynamic" bundles since these are more sensitive to changes of the different drivers across spatial scales. Moreover, any spatial scale can be eligible, but large administrative levels need caution.

The differences addressed over time showed confident generalization to advise the pros and cons of which spatial scale to use. The municipality level showed sufficient consistency with grid-scales, which may be enough to guide policy, as other studies highlighted [16,28]. However, for spatial conservation, the fine-grid scale could be needed to visualize small patch sizes. Then, as a rule, resulting from the study, ES bundles at grid scales characterized by a high level of dispersion and small patch size disappear or are imperceptible at administrative levels. Indeed, at heterogeneous landscapes, bundling becomes complex, whereas bundles are very similar across different spatial scales on homogeneous landscapes. In that sense, bundles at administrative levels tend to describe landscape multifunctionality, whereas fine-grained resolutions define more specialized bundles.

Finally, we have shown that the ES matrix and standard metrics give guidance to show the implications of choosing a method and a scale of observation in bundle assessment. To the best of our knowledge, this is the first study in which such a comprehensive step by step framework comparing "dynamic" and "static" bundles of ES has been developed. Bearing in mind the potential of bundles to support decision-making, the results might help the choice of bundling methods during the design of research projects. Our findings fill the knowledge gap on relationships between multiple ES utilizing cluster techniques robustly. Future studies should focus on a much more exhaustive list of ES. Additionally, more research is required to assess bundles at different spatial extensions and on landscapes with diverse levels of spatial heterogeneity.

Supplementary Materials: Supplementary Materials, including Tables S1–S4, Figure S5, and Tables S6–S11 are included in a separate file.

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References

1. Millennium Ecosystem Assessment. *Ecosystems and Human Well-being: Synthesis*; Millennium Ecosystem Assessment: Washington, DC, USA, 2005.
2. Liu, J.; Mooney, H.A.; Hull, V.; Davis, S.J.; Gaskell, J.; Hertel, T.W.; Lubchenco, J.; Seto, K.C.; Gleick, P.; Kremen, C.; et al. Systems integration for global sustainability. *Science* **2015**, *347*, 1258832, doi:10.1126/science.1258832.
3. Abson, D.J.; Von Wehrden, H.; Baumgärtner, S.; Fischer, J.; Hanspach, J.; Härdtle, W.; Heinrichs, H.; Klein, A.M.; Lang, D.J.; Martens, P.; et al. Ecosystem services as a boundary object for sustainability. *Ecol. Econ.* **2014**, *103*, 29–37, doi:10.1016/j.ecolecon.2014.04.012.
4. Spellerberg, I.; Vos, C.C.; Opdam, P. Landscape Ecology of a Stressed Environment. *J. Ecol.* **1993**, *81*, 599, doi:10.2307/2261549.

5. Vihervaara, P.; Rönkä, M.; Walls, M. Trends in Ecosystem Service Research: Early Steps and Current Drivers. *Ambio* **2010**, *39*, 314–324, doi:10.1007/s13280-010-0048-x.
6. Lee, H.; Lautenbach, S. A quantitative review of relationships between ecosystem services. *Ecol. Indic.* **2016**, *66*, 340–351, doi:10.1016/j.ecolind.2016.02.004.
7. Mouchet, M.A.; Lamarque, P.; Martín-López, B.; Crouzat, E.; Gos, P.; Byczek, C.; Lavorel, S. An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Glob. Environ. Chang.* **2014**, *28*, 298–308, doi:10.1016/j.gloenvcha.2014.07.012.
8. Cord, A.F.; Bartkowski, B.; Beckmann, M.; Dittrich, A.; Hermans-Neumann, K.; Kaim, A.; Lienhoop, N.; Locher-Krause, K.; Priess, J.; Schröter-Schlaack, C.; et al. Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. *Ecosyst. Serv.* **2017**, *28*, 264–272, doi:10.1016/j.ecoser.2017.07.012.
9. Howe, C.; Suich, H.; Vira, B.; Mace, G.M. Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Glob. Environ. Chang.* **2014**, *28*, 263–275, doi:10.1016/j.gloenvcha.2014.07.005.
10. Deng, X.; Li, Z.; Gibson, J. A review on trade-off analysis of ecosystem services for sustainable land-use management. *J. Geogr. Sci.* **2016**, *26*, 953–968, doi:10.1007/s11442-016-1309-9.
11. Renard, D.; Rhemtulla, J.M.; Bennett, E.M. Historical dynamics in ecosystem service bundles. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 13411–13416, doi:10.1073/pnas.1502565112.
12. Madrigal-Martínez, S.; Miralles i García, J.L. Land-change dynamics and ecosystem service trends across the central high-Andean Puna. *Sci. Rep.* **2019**, *9*, 9688, doi:10.1038/s41598-019-46205-9.
13. Stürck, J.; Schulp, C.; Verburg, P.H. Spatio-temporal dynamics of regulating ecosystem services in Europe—The role of past and future land use change. *Appl. Geogr.* **2015**, *63*, 121–135, doi:10.1016/j.apgeog.2015.06.009.
14. Hou, Y.; Lü, Y.; Chen, W.; Fu, B. Temporal variation and spatial scale dependency of ecosystem service interactions: A case study on the central Loess Plateau of China. *Landsc. Ecol.* **2017**, *32*, 1201–1217, doi:10.1007/s10980-017-0497-8.
15. Xu, S.; Liu, Y.; Wang, X.; Zhang, G. Scale effect on spatial patterns of ecosystem services and associations among them in semi-arid area: A case study in Ningxia Hui Autonomous Region, China. *Sci. Total. Environ.* **2017**, *598*, 297–306, doi:10.1016/j.scitotenv.2017.04.009.
16. Raudsepp-Hearne, C.; Peterson, G.D. Scale and ecosystem services: How do observation, management, and analysis shift with scale—lessons from Québec. *Ecol. Soc.* **2016**, *21*, doi:10.5751/es-08605-210316.
17. Rodriguez, L.C.; Pascual, U.; Niemeyer, H.M. Local identification and valuation of ecosystem goods and services from Opuntia scrublands of Ayacucho, Peru. *Ecol. Econ.* **2006**, *57*, 30–44, doi:10.1016/j.ecolecon.2005.03.022.
18. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **2009**, *12*, 1394–1404, doi:10.1111/j.1461-0248.2009.01387.x.
19. Raudsepp-Hearne, C.; Peterson, G.D.; Bennett, E.M. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc. Natl. Acad. Sci.* **2010**, *107*, 5242–5247, doi:10.1073/pnas.0907284107.
20. Tomscha, S.; Gergel, S.E. Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecol. Soc.* **2016**, *21*, doi:10.5751/es-08345-210143.
21. Lavorel, S.; Bayer, A.; Bondeau, A.; Lautenbach, S.; Ruiz-Frau, A.; Schulp, N.; Seppelt, R.; Verburg, P.; Van Teeffelen, A.; Vannier, C.; et al. Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. *Ecol. Indic.* **2017**, *74*, 241–260, doi:10.1016/j.ecolind.2016.11.015.
22. Li, T.; Lü, Y.; Fu, B.; Hu, W.; Comber, A. Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: Enhanced services while depressed synergies. *Ecol. Indic.* **2019**, *99*, 332–342, doi:10.1016/j.ecolind.2018.12.041.
23. Fan, W.; Fan, W.; Lu, N.; Xu, Z.; Liu, H.; Chen, W.; Ulgiati, S.; Wang, X.; Dong, X. Integrating Biophysical and Sociocultural Methods for Identifying the Relationships between Ecosystem Services and Land Use Change: Insights from an Oasis Area. *Sustainability* **2019**, *11*, 2598, doi:10.3390/su11092598.
24. Hamann, M.; Biggs, R.; Reyers, B. Mapping social–ecological systems: Identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use. *Glob. Environ. Chang.* **2015**, *34*, 218–226, doi:10.1016/j.gloenvcha.2015.07.008.

25. Dou, H.; Li, X.; Li, S.; Dang, D. How to Detect Scale Effect of Ecosystem Services Supply? A Comprehensive Insight from Xilinhot in Inner Mongolia, China. *Sustainability* **2018**, *10*, 3654, doi:10.3390/su10103654.
26. Cui, F.; Tang, H.; Zhang, Q.; Wang, B.; Dai, L. Integrating ecosystem services supply and demand into optimized management at different scales: A case study in Hulunbuir, China. *Ecosyst. Serv.* **2019**, *39*, 39,, doi:10.1016/j.ecoser.2019.100984.
27. Qiao, X.; Gu, Y.; Zou, C.; Xu, D.; Wang, L.; Ye, X.; Yang, Y.; Huang, X. Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. *Sci. Total. Environ.* **2019**, *651*, 218–229, doi:10.1016/j.scitotenv.2018.09.135.
28. Roces-Díaz, J.V.; Vayreda, J.; Banqué-Casanovas, M.; Díaz-Varela, E.; Bonet, J.A.; Brotons, L.; De Miguel, S.; Herrando, S.; Martinez-Vilalta, J. The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships. *Sci. Total. Environ.* **2018**, *626*, 1270–1283, doi:10.1016/j.scitotenv.2018.01.150.
29. Spake, R.; Lasseur, R.; Crouzat, E.; Bullock, J.M.; Lavorel, S.; Parks, K.E.; Schaafsma, M.; Bennett, E.M.; Maes, J.; Mulligan, M.; et al. Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. *Glob. Environ. Chang.* **2017**, *47*, 37–50, doi:10.1016/j.gloenvcha.2017.08.004.
30. Dade, M.C.; Mitchell, M.G.; McAlpine, C.A.; Rhodes, J.R. Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. *Ambio* **2018**, *48*, 1116–1128, doi:10.1007/s13280-018-1127-7.
31. Saidi, N.; Spray, C.J. Ecosystem services bundles: Challenges and opportunities for implementation and further research. *Environ. Res. Lett.* **2018**, *13*, 113001, doi:10.1088/1748-9326/aae5e0.
32. Crouzat, E.; Mouchet, M.; Turkelboom, F.; Byczek, C.; Meersmans, J.; Berger, F.; Verkerk, P.J.; Lavorel, S. Assessing bundles of ecosystem services from regional to landscape scale: Insights from the French Alps. *J. Appl. Ecol.* **2015**, *52*, 1145–1155, doi:10.1111/1365-2664.12502.
33. Van Der Biest, K.; D'Hondt, R.; Jacobs, S.; Landuyt, D.; Staes, J.; Goethals, P.; Meire, P. EBI: An index for delivery of ecosystem service bundles. *Ecol. Indic.* **2014**, *37*, 252–265, doi:10.1016/j.ecolind.2013.04.006.
34. Egoh, B.N.; Reyers, B.; Rouget, M.; Richardson, D.M. Identifying priority areas for ecosystem service management in South African grasslands. *J. Environ. Manag.* **2011**, *92*, 1642–1650, doi:10.1016/j.jenvman.2011.01.019.
35. Martín-López, B.; Iniesta-Arandia, I.; García-Llorente, M.; Palomo, I.; Casado-Arzuaga, I.; Del Amo, D.G.; Gómez-Baggethun, E.; Oteros-Rozas, E.; Palacios-Agundez, I.; Willaarts, B.; et al. Uncovering Ecosystem Service Bundles through Social Preferences. *PLoS ONE* **2012**, *7*, e38970, doi:10.1371/journal.pone.0038970.
36. Yang, G.; Ge, Y.; Xue, H.; Yang, W.; Shi, Y.; Peng, C.; Du, Y.; Fan, X.; Ren, Y.; Chang, S.X. Using ecosystem service bundles to detect trade-offs and synergies across urban–rural complexes. *Landsc. Urban Plan.* **2015**, *136*, 110–121, doi:10.1016/j.landurbplan.2014.12.006.
37. Queiroz, C.; Meacham, M.; Richter, K.; Norström, A.V.; Andersson, E.; Norberg, J.; Peterson, G.D. Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. *Ambio* **2015**, *44*, 89–101, doi:10.1007/s13280-014-0601-0.
38. Turner, K.G.; Odgaard, M.V.; Bøcher, P.K.; Dalgaard, T.; Svenning, J.-C. Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landsc. Urban Plan.* **2014**, *125*, 89–104, doi:10.1016/j.landurbplan.2014.02.007.
39. Kühne, O.; Duttmann, R. Recent Challenges of the Ecosystems Services Approach from an Interdisciplinary Point of View. *Raumforsch. Raumordn.* **2019**, 171–184, doi:10.2478/rara-2019-0055.
40. Birkhofer, K.; Diehl, E.; Andersson, J.; Ekroos, J.; Früh-Müller, A.; Machnikowski, F.; Mader, V.L.; Nilsson, L.; Sasaki, K.; Rundlöf, M.; et al. Ecosystem services-current challenges and opportunities for ecological research. *Front. Ecol. Evol.* **2015**, *2*, doi:10.3389/fevo.2014.00087.
41. Rieb, J.T.; Chaplin-Kramer, R.; Daily, G.C.; Armsworth, P.R.; Böhning-Gaese, K.; Bonn, A.; Cumming, G.S.; Eigenbrod, F.; Grimm, V.; Jackson, B.M.; et al. When, Where, and How Nature Matters for Ecosystem Services: Challenges for the Next Generation of Ecosystem Service Models. *Bioscience* **2017**, *67*, 820–833, doi:10.1093/biosci/bix075.

42. Vallet, A.; Locatelli, B.; Levrel, H.; Wunder, S.; Seppelt, R.; Scholes, R.J.; Oszwald, J. Relationships Between Ecosystem Services: Comparing Methods for Assessing Tradeoffs and Synergies. *Ecol. Econ.* **2018**, *150*, 96–106, doi:10.1016/j.ecolecon.2018.04.002.
43. Zheng, Z.; Fu, B.; Hu, H.; Sun, G. A method to identify the variable ecosystem services relationship across time: A case study on Yanhe Basin, China. *Landsc. Ecol.* **2014**, *29*, 1689–1696, doi:10.1007/s10980-014-0088-x.
44. Madrigal-Martínez, S.; Miralles i García, J.L. Understanding land use changes in the central high-Andean moist Puna. *WIT Trans. Ecol. Environ* **2019**, *238*, 175–186, doi:10.2495/sc190161.
45. Josse, C.; Cuesta, F.; Navarro, G.; Barrena, V.; Cabrera, E.; E, C.-M.; Ferreira, W.; Peralvo, M.; Saito, J.; Tovar, A. *Ecosistemas de los Andes del Norte y Centro*; Secretaría General de la Comunidad Andina, Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia, NatureServe, IAvH, LTA-UNALM, ICAE-ULA, CDC-UNALM, RUMBOL SRL: Lima, Peru, 2009; p.100.
46. Young, K.R. Andean land use and biodiversity: Humanized landscapes in a time of change. *Ann. Mo. Bot. Gard.* **2009**, *96*, 492–507, doi:10.3417/2008035.
47. Madrigal-Martínez, S.; Miralles i García, J.L. Ecosystem Services in Peru: Threats, Opportunities and Their Importance for the High-Andean Moist Puna. In *Peru in the 21st Century: Progress, Trends and Challenges*; Mariela Noles Cotito, Ed.; Nova Science Publishers: New York, NY, USA, **2020**, ISBN 9781536184983.
48. Jacobs, S.; Burkhard, B.; Van Daele, T.; Staes, J.; Schneiders, A. 'The Matrix Reloaded': A review of expert knowledge use for mapping ecosystem services. *Ecol. Model.* **2015**, *295*, 21–30, doi:10.1016/j.ecolmodel.2014.08.024.
49. Campagne, C.S.; Roche, P.; Müller, F.; Burkhard, B. Ten years of ecosystem services matrix: Review of a (r)evolution. *One Ecosyst.* **2020**, *5*, e51103, doi:10.3897/oneeco.5.e51103.
50. Burkhard, B.; Kandziora, M.; Hou, Y.; Müller, F. Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landsc. Online* **2014**, *34*, 1–32, doi:10.3097/lo.201434.
51. Drescher, M.; Perera, A.H.; Johnson, C.J.; Buse, L.J.; Drew, C.A.; Burgman, M.A. Toward rigorous use of expert knowledge in ecological research. *Ecosphere* **2013**, *4*, 83, doi:10.1890/es12-00415.1.
52. Roche, P.K.; Campagne, C.S. Are expert-based ecosystem services scores related to biophysical quantitative estimates? *Ecol. Indic.* **2019**, *106*, 105421, doi:10.1016/j.ecolind.2019.05.052.
53. Jacobs, S.; Burkhard, B. Applying expert knowledge for ecosystem services quantification. In *Mapping Ecosystem Services*; Burkhard, B.; Maes, J., Eds.; Pensoft Publishers: Sofia, Bulgaria, **2017**; p. 374.
54. INEI—National Institute of Statistics and Informatics National census. Available online: https://www.inei.gob.pe/estadisticas/censos/ (accesed on 13 January 2020).
55. Ministry of Environment. *Memoria Descriptiva del Mapa de Cobertura Vegetal del Peru*; Ministry of Environment: Lima, Peru, **2012**, ISBN 9786124605369.
56. Ministry of Environment. *Mapa Nacional de Cobertura Vegetal*; Ministry of Environment: Lima, Peru, **2015**; p. 1.
57. Haines-Young, R.; Potschin, M. Common International Clasification of Ecosystem Services CICES V5. 1. Guidance on the Application of the Revised Structure. *Fabis Consult.* **2018**; p. *53*.
58. Ryden, K. Environmental Systems Research Institute Mapping. *Am. Cartogr.* **1987**, *14*, 261–263, doi:10.1559/152304087783875930.
59. Charrad, M.; Ghazzali, N.; Boiteau, V.; Niknafs, A. Package 'NbClust'. NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. *J. Stat. Softw.* **2014**, *61*, 1–36. Available online: http://www.jstatsoft.org/v61/i06/ (accessed on 10 February 2020).
60. Development Core Team. R: A Language and Environment for Statistical Computing. *R Found. Stat. Comput.* **2016**, *1*, 409.
61. Hill, M.O. Diversity and Evenness: A Unifying Notation and Its Consequences. *Ecology* **1973**, *54*, 427–432, doi:10.2307/1934352.
62. Jost, L. Entropy and diversity. *Oikos* **2006**, *113*, 363–375.

63. Metzger, M.J.; Rounsevell, M.D.A.; Heiligenberg, H.A.V.D.; Pérez-Soba, M.; Hardiman, P.S. How Personal Judgment Influences Scenario Development: An Example for Future Rural Development in Europe. *Ecol. Soc.* **2010**, *15*, 27,, doi:10.5751/ES-03305-150205.
64. De Groot, R.; Alkemade, R.; Braat, L.; Hein, L.; Willemen, L. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecol. Complex.* **2010**, *7*, 260–272, doi:10.1016/j.ecocom.2009.10.006.
65. De Gruijter, J.J.; Bierkens, M.F.P.; Brus, D.J.; Knotters, M. Sampling for Natural Resource Monitoring. *Sampling for Natural Resource Monitoring*; Springer: Berlin/Heidelberg, Germany, **2006**.
66. Stürck, J.; Verburg, P.H. Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. *Landsc. Ecol.* **2016**, *32*, 481–500, doi:10.1007/s10980-016-0459-6.
67. Zen, M.; Candiago, S.; Schirpke, U.; Vigl, L.E.; Giupponi, C.; Michele, Z.; Sebastian, C.; Uta, S.; Lukas, E.V.; Carlo, G. Upscaling ecosystem service maps to administrative levels: Beyond scale mismatches. *Sci. Total. Environ.* **2019**, *660*, 1565–1575, doi:10.1016/j.scitotenv.2019.01.087.
68. Turner, M.G.; O'Neill, R.V.; Gardner, R.H.; Milne, B.T. Effects of changing spatial scale on the analysis of landscape pattern. *Landsc. Ecol.* **1989**, *3*, 153–162, doi:10.1007/bf00131534.
69. Verhagen, W.; Van Teeffelen, A.J.A.; Compagnucci, A.B.; Poggio, L.; Gimona, A.; Verburg, P.H. Effects of landscape configuration on mapping ecosystem service capacity: A review of evidence and a case study in Scotland. *Landsc. Ecol.* **2016**, *31*, 1457–1479, doi:10.1007/s10980-016-0345-2.
70. Scholes, R.; Reyers, B.; Biggs, R.; Spierenburg, M.; Duriappah, A. Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 16–25, doi:10.1016/j.cosust.2013.01.004.
71. Felipe-Lucia, M.R.; Comín, F.A.; Bennett, E.M. Interactions Among Ecosystem Services Across Land Uses in a Floodplain Agroecosystem. *Ecol. Soc.* **2014**, *19*, doi:10.5751/es-06249-190120.
72. Trabucchi, M.; Comín, F.A.; O'Farrell, P.J. Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services. *Reg. Environ. Chang.* **2013**, *13*, 911–926, doi:10.1007/s10113-012-0392-4.
73. Pandeya, B.; Buytaert, W.; Zulkafli, Z.; Karpouzoglou, T.; Mao, F.; Hannah, D. A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. *Ecosyst. Serv.* **2016**, *22*, 250–259, doi:10.1016/j.ecoser.2016.10.015.
74. Hein, L.; Van Koppen, C. (Kris); Van Ierland, E.C.; Leidekker, J. Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. *Ecosyst. Serv.* **2016**, *21*, 109–119, doi:10.1016/j.ecoser.2016.07.008.
75. Hou, Y.; Burkhard, B.; Müller, F. Uncertainties in landscape analysis and ecosystem service assessment. *J. Environ. Manag.* **2013**, *127*, S117–S131, doi:10.1016/j.jenvman.2012.12.002.
76. Burkhard, B.; Kroll, F.; Müller, F.; Windhorst, W. Landscapes' capacities to provide ecosystem services—A concept for land-cover based assessments. *Landsc. Online* **2009**, *15*, 1–22, doi:10.3097/lo.200915.
77. Bolliger, J.; Mladenoff, D.J. Quantifying spatial classification uncertainties of the historical Wisconsin landscape (USA). *Ecography* **2005**, *28*, 141–156, doi:10.1111/j.0906-7590.2005.03955.x.

BOOK CHAPTER

ECOSYSTEM SERVICES IN PERU: THREATS, OPPORTUNITIES AND THEIR IMPORTANCE FOR THE HIGH-ANDEAN MOIST PUNA

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Abstract

Mountain ecosystem services have gained relevance among scientists, managers, and policy-makers worldwide; but, human activities are threatening its conservation, particularly land-changes due to increased urbanization, agricultural expansion, land abandonment and deforestation. The high-Andean Puna is a representative mountain ecosystem that is facing these serious and growing challenges. The high-Andean Puna, whose main social-ecosystems consist of natural grassland, shrubland and agricultural areas, can provide multiple regulating ecosystem services related to the configuration of its land-cover features. In this context, we explored the interactions among the representative land-cover classes and its potential to provide ecosystem services in the high-Andean moist Puna. Moreover, we listed the principal disturbances that affect the suitable provision of services and we showed the Peruvian planning policies that promote ecosystem services. Our review reveals that the ecosystems identified in the moist Puna have an important role to provide regulating services, but are threatened. Therefore, decision-makers must promote spatial conservation and sustainable management processes to guarantee the supply of ecosystem services.

Keywords: ecosystem services, land-cover, mountain ecosystems, national protected areas, ecological and economic zoning, payment for ecosystem services, high-Andean moist Puna

Introduction

Ecosystem services (hereafter ES), defined as the benefits that nature provides to the population (MA 2005) has become an effective boundary object for the integration of ecosystem conservation opportunities (Abson et al. 2014). Mountain ecosystems services have gained relevance among scientists, managers, and policy-makers worldwide (Egarter et al. 2017; Grêt-Regamey, Brunner, and Kienast 2012; Sun et al. 2016; Madrigal-Martínez and Miralles i García 2019a). However, human activities are threatening its conservation (MA 2005), particularly land-changes due to increased agricultural intensification, urbanization and deforestation.

The high-Andean Puna is a representative mountain ecosystem that is facing these serious and growing challenges. This ecosystem is composed by two well-defined phytogeographic regions: the moist Puna and the xerophytic Puna (Josse et al. 2009). The moist Puna (Peru and Bolivia) has been occupied and its resources profited during several millennia by Andean civilizations (Josse et al. 2009; Young 2009). This mountain

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environment, where its main social-ecosystems consist of natural grassland, shrubland and agricultural areas, can provide multiple regulating ES related to the configuration of its land-cover features (Madrigal-Martínez and Miralles i García 2019a). Consequently, ES in the moist Puna must be sustained and promoted. In this sense, the Peruvian government has developed several policy instruments to promote sustainable land use. Almost all these instruments are led by public actors in each stage of the regulatory process, except the payments for ES which is a mixed public-private initiative, engaging nongovernment organizations and private companies (e.g., water management companies).

Table 1. Description and examples of the selected ES studied in the moist Puna

Ecosystem service	Description
Water purification	Regulation of the chemical condition of freshwaters by living processes. e.g., Use of buffer strips along water courses to remove nutrients in runoff.
Regulation of soil erosion	Control of erosion rates. e.g., The capacity of vegetation to prevent or reduce the incidence of soil erosion.
Water flow regulation	Hydrological cycle and water flow regulation (Including flood control) e.g., The capacity of vegetation to retain water and release it slowly.
Soil quality	Decomposition and fixing processes and their effect on soil quality. e.g., Decomposition of plant residue; N-fixation by legumes.
Global climate regulation	Regulation of chemical composition of atmosphere. e.g., Sequestration of carbon in tropical peatlands.

(Elaborated by the Authors - drawn from Haines-Young and Potschin 2018)

In this chapter of the book Perú in the 21st Century, we focus on the main concerns about five regulating ES provided by the moist Puna (Table 1). Some of the topics included are broad and need consideration in greater detail (e.g., *Main causes of ecosystem disturbances in the moist Puna*). First, we describe the features and the spatial distribution of the land-cover units within the moist Puna. We highlight the relevant extension of the natural and semi-natural classes that dominate the landscapes of the region. Second, we conduct an in-depth analysis of ES studies conducted across the moist Puna to demonstrate its potential to supply regulating services. We highlight the evaluation methods used and the interactions found between the land-cover units and each ES. Third, we identify the main disturbances that impact ecosystems and affect the suitable provision of services. Finally, we show the Peruvian planning policies that promote ES. We spatially represent these initiatives within the study site.

The Moist Puna

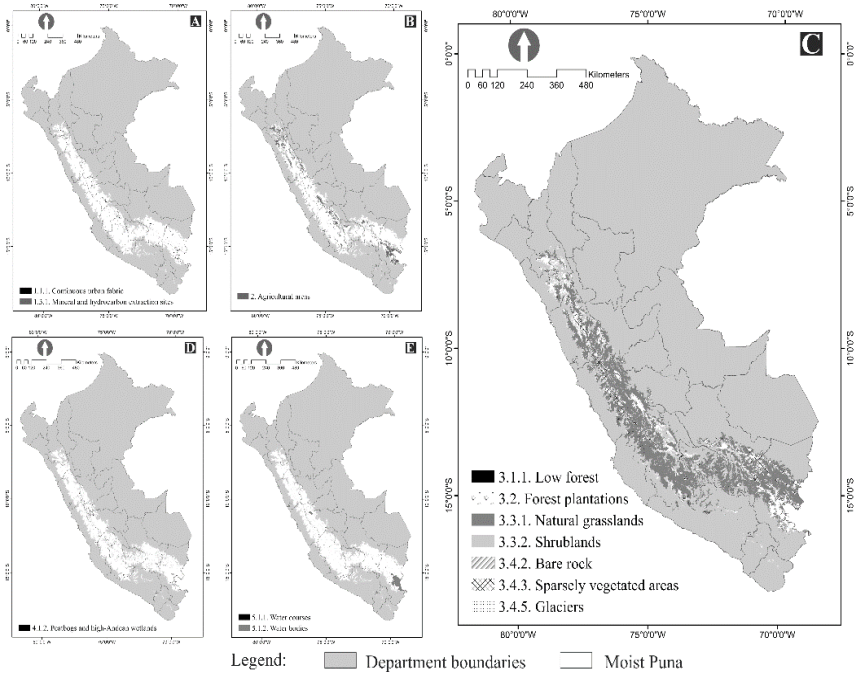

Figure 1. Maps of the Peruvian moist Puna comprising the different Corine Land Cover categories (A, B, C, D, E). (A) artificial surfaces; (B) agricultural areas; (C) forests and semi-natural areas; (D) wetlands; (E) water bodies. (Elaborated by the Authors)

The high-Andean moist Puna has an extension of 208,865 km^2 characterized by different ecosystems classified in thirteen land-cover categories (Figure 1). These land-cover units were identified through the standardized nomenclature of the Corine Land Cover (CLC) for Peru using the official flora cover map from 2013 (Ministry of Environment 2015). The units include two categories linked to artificial surface (continuous urban fabric and mineral extraction sites), one class related to agricultural areas, seven attributes associated to forests and semi-natural areas (low forest, forest plantation, natural grassland, shrublands, bare rock, sparsely vegetated areas and glaciers), one item linked to wetlands (peatbogs and high-Andean wetlands) and, finally, two classes linked to water bodies (water courses and water bodies).

Artificial Surfaces

The land covered in 2013 by population settlements and mining sites was the least extensive (Figure 1A), occupying 486 km^2. The unit of continuous urban fabric (369 km^2) comprised many small urban centers and six major cities: Cajamarca in the North; Huancayo and Ayacucho in the center; and Cusco, Puno and Juliaca in the South. Furthermore, the larger areas with open-pit extraction of minerals (117 km^2) are mainly located in the Center and the North of the moist Puna.

Agricultural Areas

Agricultural areas in the moist Puna (Figure 1B) covered 27,450 km^2 (13% of the total territory). This land was mainly dominated by extensive non-permanent crops

distributed in three huge productive zones (the North, Center, and South of the moist Puna). The North zone comprised of several headwater basins in the administrative departments of Cajamarca, La Libertad, Ancash, and Huanuco. The Center area included two high-Andean basins (Mantaro and Pampas) within the departmental boundaries of Junin, Huancavelica, Ayacucho, and Apurimac. Finally, the South zone included the agricultural extents situated in the hydrographic region of Titicaca (Puno department).

Forests and Semi-Natural Areas

The moist Puna was dominated by seven semi-natural or natural ecosystems (Figure 1C) that occupy 170,012 km^2 (81% of the total territory). Landscapes covered by the low forest category were 1174 Km^2 (1% of the moist Puna), and were composed of three types of forest ecosystem: the inter-Andean xeric montane forest and shrublands, the low high-Andean forest, and the high-montane low forest and shrublands (Josse et al. 2009). Whereas forest plantations were characterized by *pinus* and *eucalyptus* species, covering just 636 Km^2.
Two classes of shrub and/or herbaceous vegetation associations were spatially distributed across the moist Puna and associated with extensive South-American camelids cattle activity. Natural grassland cover was the largest unit (118,929 km^2, 57% of the territory), composed of high-Andean grassland, Puna meadow, and *tolar* spp (Ministry of Environment 2015). Whereas shrublands cover (35,825 km^2, 17% of the territory), and were characterized by inter-Andean xeric montane shrublands, inter-Andean xeric shrublands, high-montane shrublands, and high-Andean edaphic-xerophilous shrublands (Josse et al. 2009).
Finally, three land-cover units were classified as open spaces with little or no vegetation: bare rock, sparsely vegetated areas, and glaciers. Bare rock extents (67 km^2) and sparsely vegetated areas (11,737 km^2) were represented by high-Andean saxicolous and subnivean congeliturbate vegetation (Josse et al. 2009), respectively. Glaciers coverages (1644 km^2) included areas of solid or melting ice and snow.

Wetlands

Peatbogs and high-Andean wetlands covered 4210 Km^2 (2% of the territory) spatially distributed in the Center and the South of the moist Puna (Figure 1D). This category is composed of four types of ecosystems: bofedales, high-Andean hygrophytic grassland, high-montane hygrophytic grassland, and high-Andean aquatic and marshy vegetation (Josse et al. 2009).

Water Bodies

Two units classified as water bodies were identified in the moist Puna (Figure 1E). The first unit was natural water courses (144 km^2), serving as water drainage channels primarily represented by Marañon river in the North and Mantaro river in the Center. While, the second unit was represented by natural lagoons and lakes (6563 km^2, 3% of

the moist Puna), which had as its main significant features the Junin lake and the Titicaca lake.

Ecosystem Services Knowledge of the Moist Puna

The interactions among representative land-cover classes and its potential to provide five regulating ES in the moist Puna were assessed with an in-depth analysis of published scientific literature including peer-reviewed journal articles from 2002 to 2019 indexed in Web of Science and Scopus, or found in Google Scholar (Table 2). The five selected ES include site-specific services identified by the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018); two services related to the mediation of flows (regulation of soil erosion and water flow regulation); one ES related to filtration, sequestration, storage or accumulation by ecosystems (water purification) and, finally, two services linked to the maintenance of physical, chemical, and biological conditions (soil quality and global climate regulation).

Table 2. Ecosystem services and the study that evidenced their relationship with land-cover units in the moist Puna

Ecosystem service	Study and land-cover units
Water purification	(Madrigal-Martínez and Miralles i García 2019a): NG, LF, SL, PhAWL, WB, WC; (Custodio et al. 2018): WB; (Cochi et al. 2018): PhAWL; (Salvador, Monerris, and Rochefort 2014): PhAWL.
Regulation of soil erosion	(Madrigal-Martínez and Miralles i García 2019a) : NG, LF, FP, SL, PhAWL; (Duchicela et al. 2019): NG; (Blancas, La Torre-Cuadros, and Carrera 2018): NG; (Oscanoa and Flores 2016): NG; (Rodríguez, Pascual, and Niemeyer 2006): SL; (Fjeldså 2002): LF.
Water flow regulation	(Madrigal-Martínez and Miralles i García 2019a): NG, LF, SL, Gl, PhAWL, WB, WC; (Blancas, La Torre-Cuadros, and Carrera 2018): PhAWL, NG; (Cochi et al. 2018): PhAWL; (Hartman, Bookhagen, and Chadwick 2016): PhAWL; (Maldonado 2014): PhAWL; (Baraer et al. 2009): Gl; (Vuille et al. 2008): Gl; (Mark and Seltzer 2003): Gl; (Fjeldså 2002): LF
Soil quality	(Madrigal-Martínez and Miralles i García 2019a): NG, LF, SL, PhAWL; (Duchicela et al. 2019): NG; (Cochi et al. 2018): PhAWL; (de Valença et al. 2017): FP, LF, NG; (Salvador, Monerris, and Rochefort 2014): PhAWL; (Jameson and Ramsay 2006): LF; (Fjeldså 2002): LF
Global climate regulation	(Madrigal-Martínez and Miralles i García 2019a): NG, FP, LF, SL, PhAWL; (Cochi et al. 2018): PhAWL; (Rolando et al. 2017): NG; (Oliveras et al. 2014): NG; (Salvador, Monerris, and Rochefort 2014): PhAWL; (Maldonado 2014): PhAWL; (Vásquez, Ladd, and Borchard 2014): LF; (Segnini et al. 2010): PhAWL; (Gibbon et al. 2010): NG; (Zimmermann et al. 2010): NG, SL

(Elaborated by the Authors)
Land-cover units and abbreviations: Agricultural areas (AA), Low forest (LF), Forest plantation (FP), Natural grassland (NG), Shrublands (SL), Glaciers (Gl), Peatbogs and high-Andean wetlands (PhAWL), Water bodies (WB), Water courses (WC).

Our search included the terms “ecosystem services” and “Peru” or “Bolivia”, and either “Puna”, “Andes”, or “Andean”. The revision of the two databases identified 57 results and we analyzed them for their assessment of one or more of the five regulating ES across the moist Puna. Most of the studies were excluded (50) because one or two main reasons: (I) they were not exactly conducted in the moist Puna, or (II) their assessment did not concretely specify a land-cover unit or deal with ES supply. The review articles were excluded, but we searched within the articles cited that focused on the moist Puna to extract data. We compiled the final inventory of studies through

a search in Google Scholar. Table 3 list the main characteristics of the 22 articles that were analyzed using descriptive statistics.

Water Purification

Four studies confirmed that several ecosystems in the moist Puna have the capacity to maintain chemical composition of freshwater to ensure favorable living conditions for biota (Table 2). Peatbogs and high-Andean wetlands were ecosystems that were the most researched on, with three analyses that were conducted between 2014 and 2019 using sampling (n = 2) and expert-knowledge (n = 1) methods (Table 3). Shrublands and water bodies ecosystems were studied by two research initiatives separately between 2006 and 2019 using sampling (n = 1) and expert-knowledge (n = 1) methods (Table 3). Low forest, natural grasslands and water courses also were assessed during 2019 by an expert-based estimation technique.

Madrigal-Martinez and Miralles i Garcia's (2019) research determined six main land-use categories that supply water purification: low forest, natural grasslands, shrublands, peatbogs and high-Andean wetlands, water courses and water bodies. They found that peatbogs and high-Andean wetlands showed the highest potential supply, and the water courses indicated the lowest.

Cochi et al. (2019) and Salvador Monerris, and Rochefort (2014) developed studies focused on the vegetation diversity of the high-Andean wetlands. Both studies indicated that the great capacity of these ecosystems was reduced by human-disturbances (grazing, peat extraction and roads). Custodio et al. (2018) studied the conditions of water quality in high-Andean lakes, and discovered that anthropogenic activities influenced the properties of the aquatic environment. These threat actions are detailed in the section *Main causes of ecosystem disturbances in the moist Puna.*

Regulation of Soil Erosion

The reviewed studies (n = 6) demonstrated that ecosystems with suitable vegetation cover are related to efficient soil erosion prevention (Table 2). Natural grasslands got the highest quantity of researches (n = 4), whereas low forest landscapes (studied in two cases) expressed the highest capacity to supply the service according to Madrigal-Martinez and Miralles i Garcia (2019). Shrublands (n = 2), bofedales (n = 1) and forest plantation (n = 1) showed the capacity to reduce soil erosion in three studies. Sampling techniques (n = 2), expert knowledge approach (n = 2) and surveys (n = 2) were the methods applied to evaluate erosion control (Table 3).

Blancas, La Torre-Cuadros, and Carrera (2018) consulted twenty experts that identified the capacity of tolar ecosystems (Andean grassland according to the Ministry of Environment (2015)) to prevent soil erosion. This function was also established by 43 experts in the moist Puna study developed by Madrigal-Martinez and Miralles i Garcia (2019). Duchicela et al. (2019) and Oscanoa and Flores (2016) proved that rehabilitation practices improved vegetation cover (grassland), reducing soil loss.

Furthermore, Fjeldså (2002) noted that local communities agreed that the regeneration of dense low forest (*Polylepis* spp.) is needed on high elevations and steep slopes for protecting their infrastructure against persistent landslides. Similarly, Rodríguez, Pascual, and Niemeyer (2006) identified, through semi-structured interviews with peasants, that shrublands (*Opuntia* spp.) provide laminar erosion control on sloping environments. Specialists also indicated that shrublands and bofedales ensure the stability of the soil (Madrigal-Martínez and Miralles i García 2019a). However, *Eucalyptus* plantations showed a high potential supply of soil erosion prevention (Madrigal-Martínez and Miralles i García 2019a), even if, planting this species in areas were soil erosion and water scarcity are critical factors should be avoided (Fjeldså 2002).

Water Flow Regulation

The studies demonstrated that moist Puna ecosystems in a good condition guarantee the suitable regulation of water flow (Table 2). High-Andean wetlands (n = 5) and glaciers (n = 4) were the ecosystems most studied and expressed the highest capacity to supply the service (Madrigal-Martínez and Miralles i García 2019a). Whereas water bodies (n = 1) and low forest (n = 2) were the categories studied the least, but had very high potential supply (Madrigal-Martínez and Miralles i García 2019a). Furthermore, natural grasslands and shrublands (with high potential supply) were also considered by two and one study cases, respectively.
Water flow regulation was evaluated with four different methods (Table 3). Four studies conducted research using sampling techniques, whereas expert knowledge, surveys and model approaches were utilized by two studies each. Expert judgments coincided in the capacity of natural grasslands and peatbogs and high-Andean wetlands to supply the service (Madrigal-Martínez and Miralles i García 2019a; Blancas, La Torre-Cuadros, and Carrera 2018). Similarly, sampling technics assessed that bofedal ecosystems regulate the downhill flux of water (Cochi et al. 2018; Hartman, Bookhagen, and Chadwick 2016; Maldonado 2014). The function of glaciers, as very efficient runoff buffers, was mainly evaluated with modeling methods (Baraer et al. 2009; Vuille et al. 2008; Mark and Seltzer 2003) and expert experience (Madrigal-Martínez and Miralles i García 2019a).
Local communities have consensus that the vegetation cover provided by the low forest (*Polylepis* spp.) could ensure the water supply to the population due to the capacity of these ecosystems to store the water in the loose and fertile soil (Fjeldså 2002). This significant role of the low forest also was confirmed by specialists (Madrigal-Martínez and Miralles i García 2019a).

Soil Quality

Mainly five types of land-cover (low forest, forest plantation, shrublands, natural grasslands and peatbogs, and high-Andean wetlands) were identified as the

ecosystems that enhance the quality of soils (Table 2). Low forest, natural grasslands and peatbogs, and high-Andean wetlands showed the highest potential supplying the service (Madrigal-Martínez and Miralles i García 2019a), whereas forest plantations of *Eucalyptus* spp indicated the lowest overall soil fertility (de Valença et al. 2017). Natural grasslands landscapes also supported more diverse soil communities that improved soil fertility when they were slightly disturbed (Duchicela et al. 2019; de Valença et al. 2017).
Soil quality was primarily measured with sampling methods (n = 4), interviews with local farmers (n = 2) and consulting with experts (n = 1) (Table 3). Local farmers indicated that areas covered by an open canopy of low forest (mainly studies focused on *Polylepis* spp.) have rich soils (Fjeldså 2002), and are suitable to cultivating crops (Jameson and Ramsay 2007). Likewise, a sampling study confirmed that levels of organic matter are high in forest soils, more than in pasture extents (de Valença et al. 2017), also agreed by experts (Madrigal-Martínez and Miralles i García 2019a). Two studies carried out with sampling methods demonstrated high levels of organic matter in soils of peatbogs and high-Andean wetlands (Cochi et al. 2018; Salvador, Monerris, and Rochefort 2014).

Global Climate Regulation

Ten studies demonstrated that different types of ecosystems in the moist Puna have a capacity to serve as buffers against climate change by storing carbon stocks in vegetation and soil (Table 2). Peatbogs and high-Andean wetlands reviewed in five study cases were found to have the highest potential supply as carbon sinks (Madrigal-Martínez and Miralles i García 2019a). Likewise, five other analyses assessed the importance of natural grasslands as carbon sequesters in soil (Table 2). Mainly, these studies found that the amounts of carbon storage in the soil were higher than in the above-ground biomass, using sampling (n = 9) techniques (Table 3).

Table 3. List of publications included in the analysis conducted and found in two databases (Web of Science and Scopus) and an academic searcher (Google Scholar)

Ecosystem services	Study, Location (scale)	Reference, Type of data, Method(s)
WQ, WFR, RSE, SQ, GCR	Land-change dynamics and ecosystem service trends across the central high-Andean Puna (provincial)	(Madrigal-Martínez and Miralles i García 2019a), Primary data, Expert knowledge
RSE, SQ	Indicators for assessing tropical alpine rehabilitation practices, the department of Huancavelica (local)	(Duchicela et al. 2019), Primary data, Sampling and monitoring
WQ	Quality of the aquatic environment and diversity of benthic macroinvertebrates, the Mantaro river basin, Junin (local)	(Custodio et al. 2018), Primary data, Sampling
WFR, RSE	Future of ecosystem services in a mountain protected area, Salinas and Aguada Blanca National Reserve (local)	(Blancas, La Torre-Cuadros, and Carrera 2018), Primary data, Expert knowledge
WFR, WQ, GCR	Grazing, plant species composition and water presence on bofedales, central part of the Cordillera Real, Bolivia (local)	(Cochi et al. 2018), Primary data, Sampling
GCR	Soil organic carbon stocks and fractionation under different land uses, Provinces of Junin and Yauri in the Department of Junín (local)	(Rolando et al. 2017), Primary data, Sampling

SQ	Land use as a driver of soil fertility and biodiversity across an agricultural landscape, community of Quilcas, located near Huancayo in the Junín department of central Peru (local)	(de Valença et al. 2017), Primary data, Sampling
WFR, RSE	Improvement of hydrology function of soils, rural community of Cordillera Blanca – Huaraz (local)	(Oscanoa and Flores 2016), Primary data, Sampling and monitoring
WFR	The effects of check dams and other erosion control structures on the restoration, Ayllu Majasaya-Aransaya-Urunsaya in the Tapacarí Province, Department of Cochabamba, Bolivia (local)	(Hartman, Bookhagen, and Chadwick 2016), Primary data, Sampling and monitoring, Remote Sensing
GCR	Andean grasslands are as productive as tropical cloud forests, South-eastern Peruvian Andes (local)	(Oliveras et al. 2014), Primary data, Sampling

Table 3. (Continued).

Ecosystem services	Study, Location (scale)	Reference, Type of data, Method(s)
WQ, SQ, GCR	Peatlands of the Peruvian Puna ecoregion, central and southern Peruvian Puna (local)	(Salvador, Monerris, and Rochefort 2014), Primary data, Sampling
GCR, WFR	An introduction to the bofedales, Peruvian High Andes (national)	(Maldonado Fonkén, 2014), Primary data, Sampling and monitoring
GCR	Carbon storage in a high-altitude Polylepis woodland, Nor Yauyos Cochas National Park (local)	(Vásquez, Ladd, and Borchard 2014), Primary data, Sampling
GCR	Spectroscopic assessment of soil organic matter in wetlands, Huayllapata, Puno (local)	(Segnini et al. 2010), Primary data, Sampling
GCR	Ecosystem carbon storage across the grassland–forest transition, high Andes in Manu National Park (local)	(Gibson et al. 2010), Primary data, Sampling
GCR	Soil carbon stocks across the tree line in the Peruvian Andes, western border of the Manu National Park (local)	(Zimmermann et al. 2010), Primary data, Sampling
WFR	Characterizing contributions of glacier melt and groundwater, Cordillera Blanca (local)	(Baraer et al. 2009), Primary data, Models
WFR	Climate change and tropical Andean glaciers, Cordillera Blanca (local)	(Vuille et al. 2008), Secondary data, Models
SQ	Changes in high-altitude Polylepis forest cover and quality, Cordillera de Vilcanota, Cusco (local)	(Jameson and Ramsay 2007), Primary data, Interviews
RSE	Ecosystem goods and services from Opuntia scrublands, Huamanga province (local)	(Rodríguez, Pascual, and Niemeyer 2006), Primary data, Surveys
WFR	Tropical glacier meltwater contribution to stream discharge, Cordillera Blanca (local)	(Mark and Seltzer 2003), Primary data, Models
WFR, RSE, SQ	Polylepis forests, high-Andean region (national)	(Fjeldså 2002), Primary data, Surveys, sampling, remote sensing

(Elaborated by the Authors)
Regulating ecosystem service types and abbreviations: water purification (WP), regulation of soil erosion (RSE), water flow regulation (WFR), soil quality (SQ) and global climate regulation (GCR)

In this sense, Vásquez, Ladd, and Borchard (2014) determined that the low forest stored 10% of the total ecosystem carbon stock in canopies (90% in soil). Similarly, Gibbon et al. (2010) quantified that carbon in Puna grassland was mainly stored belowground. Segnini et al. (2010) determined that soil C stocks are higher in permanently flooded bofedales than seasonally bofedales, and differences were higher in the upper layers. Moreover, the capacity of bofedales to accumulate carbon in the soil was also shown in many studies (e.g., Cochi et al. 2018; Salvador, Monerris, and Rochefort 2014; Maldonado 2014).

Total soil carbon stock determined in shrubland and grassland landscapes showed similar quantities (Zimmermann et al. 2010). Also, natural grasslands accumulated soil

carbon stocks similar to the amounts of cloud forests (Oliveras et al. 2014). Rolando et al. (2017) confirmed the importance of Puna grasslands as soil carbon reservoirs. Furthermore, experts expressed the high potential of natural grasslands to supply the service (Madrigal-Martínez and Miralles i García 2019a).

Core Results

Our review reveals an increasing attention on high-Andean moist Puna ecosystems in the last decade. The majority (90%) of the studies were carried out after 2005, the year in which the second Millennium Assessment study was conducted. In the 22 papers included in the literature review (Table 3), we found a total of 36 quantified ES. ES were mainly measured with sampling techniques (Figure 2a). Expert knowledge (23%) was predominantly used for water flow regulation, regulation of soil erosion and soil quality services. Models, which were the least employed methodology (14%), were mainly used to quantify regulation of water flow in glaciers.
Nineteen studies evaluated ES on the local level, whereas only one research was carried out at the provincial level (Figure 2b). The five regulating ES have received some attention, according to our analysis (Figure 2c). The water flow regulation and global climate regulation services received the greatest attention, with ten and nine studies respectively, whereas purification of water was studied in only four scientific studies.
Eight land-cover categories received some attention in one or more studies (Figure 2d). Natural grasslands and peatbogs and high-Andean wetlands were the most studied land-cover units, whereas water courses, water bodies, and forest plantation were the least. Glaciers were considered by its provision of water flow regulation, whereas low forest landscapes obtained more interest by its capacity to improve soil quality.

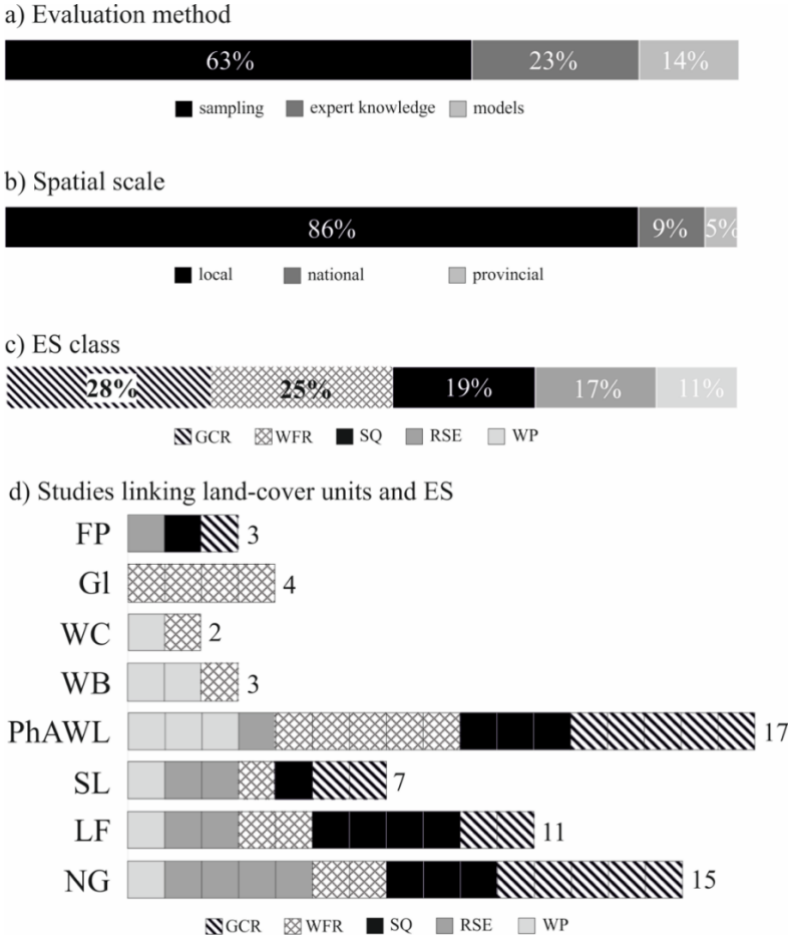

Figure 2. Percentage (a, b, c) of the studies reviewed, and total links (d) between the land-covers and the ecosystem services, in the moist Puna. Abbreviations are detailed in former sections of the chapter. (Elaborated by the Authors)

Main Causes of Ecosystem Disturbances in the Moist Puna

Grazing and Burning

Low forest distribution in the moist Puna has been isolated in hilly landscapes where livestock normally do not roam and fire cannot spread (Fjeldså 2002). These activities represent a continuing threat to the forest declining in density, size, and straightness of trees over time (Madrigal-Martínez and Miralles i García 2019a; Jameson and Ramsay 2007). Also, high-Andean wetlands are disturbed by overgrazing, which was more severe with non-native animals (cattle, pigs, and horses) (Salvador, Monerris, and Rochefort 2014). Moreover, this heavy grazing pressure on bofedales reduces their plant species composition and relative abundance (Cochi et al. 2018).
Puna natural grasslands are also disturbed by grazing and burning activities that negatively affect soil carbon stocks (Gibson et al. 2010), whereas only fire was related to lower N stocks (Zimmermann et al. 2010). Furthermore, the decrease of grassland cover produces an increase in soil temperature, accelerating soil organic matter decomposition (Zimmermann et al. 2010; Hofstede 1995). Meanwhile, Puna grassland expansion was related to the persistent dried up process of high-Andean wetlands (Madrigal-Martínez and Miralles i García 2019b).

Deforestation

Felling trees for fuel and construction was considered by local farmers to be the main threats to low forest (*Polylepis* spp.) (Jameson and Ramsay 2007). These activities together with the actions mentioned in the former section showed a trend of forestland decrease following shrublands growth. This pattern of deforestation was related to high population density, low family income and education, whereas forest recovery was linked to low population density and the improvement of educational standards (Madrigal-Martínez and Miralles i García 2019b).

Urbanization

In the moist Puna, urban sprawl is a land-change dynamic with the least effect on agricultural and grazing lands (Madrigal-Martínez and Miralles i García 2019a). Likewise, population growth impacts soil quality, pushing farmers to crop at higher elevations with less favorable conditions (Fonte et al. 2012; Skarbø and VanderMolen 2016). These higher elevations demand larger quantities of water services (energy and freshwater) putting a strain on glaciers and freshwater ecosystems.

Agricultural Expansion

Agricultural expansion transformed many lands of low forest, natural grasslands, shrublands, and peatbogs and high-Andean wetlands (Madrigal-Martínez and Miralles i García 2019b). Puna grassland is being converted into farming lands in higher altitudes due to better conditions as a consequence of climate change (Skarbø and VanderMolen 2016). This activity, with extensive impact on the landscape, has heavy pressures on freshwater ecosystems.

Planning Policies to Promote Ecosystem Services

Peru developed several policy instruments to accomplish spatial conservation and sustainable management processes of ES (Table 4). In the moist Puna, the areas regulated under any type of instrument occupy 39,526 km^2 (19% of the territory) (Figure 3).

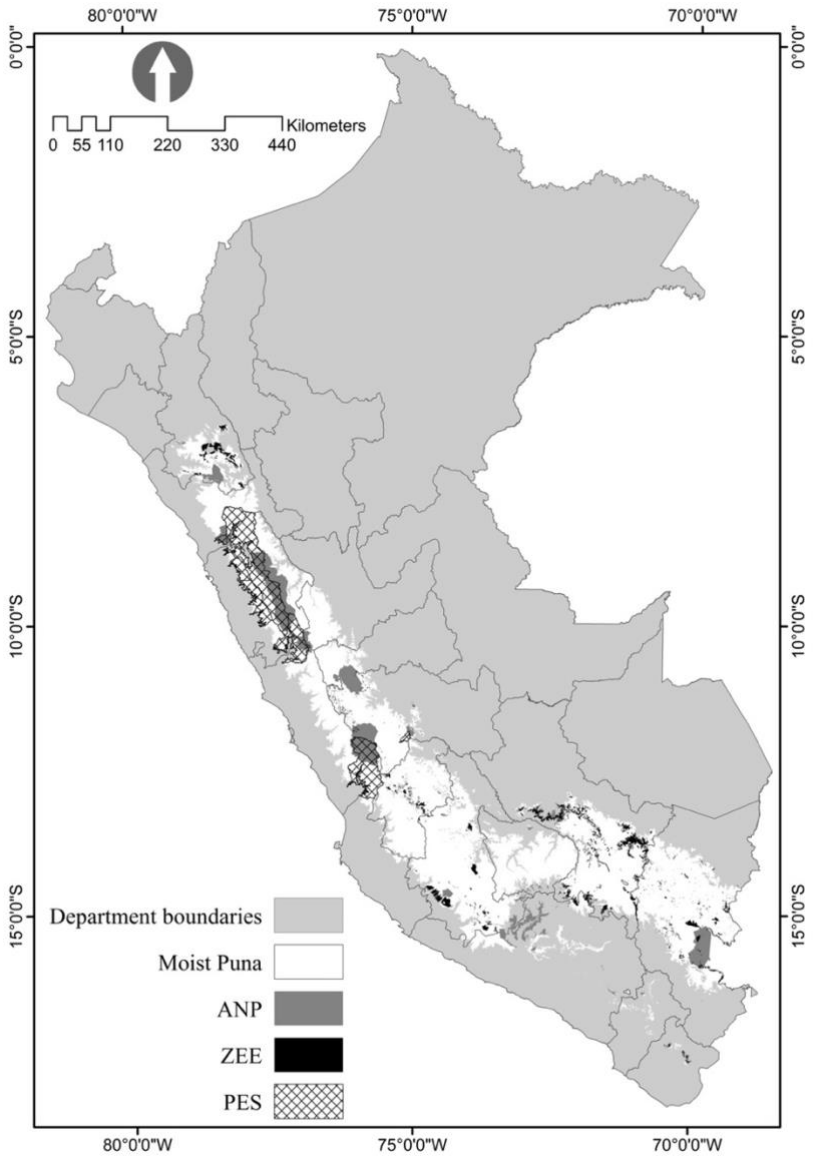

Figure 3. Map of Peru including the spatial distribution of the land planned by the instruments that contribute to promote ecosystem services in the moist Puna. Instrument types and abbreviations: Natural Protected Areas (ANP), Ecological and Economic Zoning (ZEE), and Payment for Ecosystem Services (PES). (Elaborated by the Authors)

Table 4. Types and characteristics of the instruments developed in Peru that contribute to promote ecosystem services

Instrument	Main purpose	Policy mechanism	Scope	Year
National protected areas (ANP)	Spatial conservation	Mandatory restrictions	National	1997
Ecological and economic zoning (ZEE)	Land use planning	Advice of land-use	Departmental and provincial	2006
Study of ecosystem services for land planning (ESS)	Land use planning	Advice of land-use	Departmental and provincial	2013
Payment for ecosystem services (PES)	Spatial conservation and land use planning	Incentive	National	2014
Public investment in biodiversity and ecosystem services (BES)	Restoration and spatial conservation	Incentive	National	2015

Forestry zoning (ZF)	Land use planning	Mandatory restrictions	Departmental	2016

(Elaborated by the Authors)

National Protected Areas

The national protected areas (ANP) have the following main objectives related to the promotion of ES: (1) to maintain and manage the resources of flora and wildlife in order to ensure a stable and sustainable production (for food production, recreational and tourism development); (2) to maintain genetic resources to develop options for the improvement of production systems and to support scientific, technological and industrial research; (3) to maintain and manage the functional conditions of watersheds, in order to ensure water collection, flow, quality, and erosion control; (4) to provide opportunities for educational activities, as well as for the development of scientific research (Law nº 26834).
The main ES that provide these areas are food (fish and meat), clean water supply, water flow regulation, and global and local climate regulation (Ministry of Environment and SERNANP 2016). Peru has a total of 139 ANP belonging to the national system of natural protected areas that correspond with 17% of the national territory (SERNANP 2019). However, by 2021, Peru plans to spread national protected areas to at least 17% of the land and 10% of the marine environment (Ministry of Environment 2014). In the moist Puna, there is 10719 km^2 (5% of the territory) declared as ANP and 7983 km^2 (4% of the territory) delimited as a buffer zone (Figure 3).

Ecological and Economic Zoning

The ecological and economic zoning (ZEE) is a technical instrument to guide decision making on the best uses of different territories (ZEE regulation, Supreme Decree n° 087-2004-PCM). This instrument delimits spatial zones with a degree of internal homogeneity defined by the most important physical, biological, and socioeconomic characteristics inventoried in the territory of study. The spatial zones are management land units that are classified into five categories according to their potentials and limitations. One of these categories defines the areas with high biodiversity and essential ecological processes that include the ANP, hillside protected lands, wetland areas, headwaters of the river basin and adjacent areas to the riverbanks (Council Decree n° 010-2006-CONAM/CD).
Seven departments (Cajamarca, Junin, Huancavelica, Ayacucho, Cusco, Puno, and Tacna) that include areas of moist Puna within their territory concluded their ZEE by 2017 (Ministry of Environment 2017) and defined 7554 km^2 (4% of the moist Puna) as conservation zones, in addition to the ANP (Figure 3). These areas are mainly characterized by high extents of basin headwaters, nival zones, native-forest lands and unique ecosystems with very high biodiversity.

Study of Ecosystem Services for Land Planning

The study of ecosystem services for land planning (ESS) aims to characterize the current situation and the state of conservation of the main ES available in a given geographical area (Ministry Resolution nº 135-2013-MINAM). It is done by the department level authority that has previously approved the ZEE. Of the thirteen departments that completed the ZEE by 2017, none accomplished the ESS.

Payment for Ecosystem Services

In Peru, payment for ecosystem services (PES) is regulated by the law of remuneration mechanisms for ecosystem services (Law nº 30215). These compensation mechanisms, resulting from voluntary agreements, establish conservation, recovery and sustainable use actions to ensure the permanence of ecosystems. The agreement is between providers and remunerators. The providers are the actors that, through technically feasible actions, contribute to maintaining the sources of ES. Whereby, the remunerators are the actors that pay the providers through an exchange of the economic, social, or environmental benefits obtained through the ES (Law nº 30215). By 2016, the rules included hydrological and carbon sequestration services. Hydrological services encompass water provisions and regulation, soil erosion prevention, and water purification. By 2019, eighteen hydrological initiatives of PES were registered in Peru (Ministry of Environment 2019), seven of which were located in the moist Puna. These seven mechanisms have their scope of action covering over 19,948 km^2 (10% of the moist Puna), mainly located in the northwest of the territory (Figure 3). There were no mechanisms on carbon sequestration service registered in the moist Puna by the year 2019 (Ministry of Environment 2019).

Public Investment in Biodiversity and Ecosystem Services

By 2019, eighty-five public investment projects aimed to improve ecosystems and to recover ES (water flow regulation and soil erosion prevention) in Peru. However, at the moment they are in the initial phases (Ministry of Economy and Treasury 2019). Many of these initiatives would benefit moist Puna landscapes.

Forestry zoning

The forestry zoning (ZF) is a mandatory technical and participatory process of forest land demarcation. The ZF determines the potential and limitations for direct and indirect use of forest ecosystems and other ecosystems of wild vegetation. It includes the maintenance of its ability to provide ecosystem goods and services, defining alternatives for the use of forest resources and wild fauna (Law 29763). This instrument identifies, in a given territory, four land-use categories. The fourth category delimits areas (agroforestry zones and residuary forest) that need special management

due to their importance providing ES. By 2019, there were no ZFs completed in the moist Puna (SERFOR 2019).

Conclusion

The ecosystems identified in the moist Puna have an important role in providing regulating services. Among them, low forests, shrublands, natural grasslands, and peatbogs and high-Andean wetlands are the ecosystems that dominate the landscape. Furthermore, glaciers denoted a high potential supply of regulating water flow, whereas water bodies stood out for their capacity to purify water. These semi-natural areas have the capacity to supply all the services studied when they are in optimal conditions. However, these ecological functions are continuously threatened by human interventions.

The main threats that have to face the moist Puna are grazing and fire, the farming expansion, and urbanization processes. These two-former land-change dynamics demand freshwater subjecting to excessive pressure in the event of inefficient management of the resources provided by glaciers and water bodies. Whereas grazing and fire are degrading the soil conditions, with the following decrease effect in the supply of regulating and provisioning services, the agricultural expansion is transforming semi-natural areas causing the trade-off of regulating services by provisioning services. In that sense, urban expansion has a negative effect on ecosystem services, but more dramatically when there are no planning directives.

Despite all these threats to ecosystems, we find strengths based on the spatial planning initiatives that promote the provision of ES in the moist Puna. To the best of our knowledge, the Peruvian government is the first state in South America that regulated the PES mechanism by Law. This legal support offers to providers of ES a security related to the financial incentive that, through an agreement, could enlarge the extents of ecosystems under sustainable use. Added to this, there is the institutional strength offered by the Ministry of the Environment and the National Superintendence of Sanitation Services, that give stable conjuncture and promote the PES mechanism.

However, there are some weaknesses related to the Peruvian land-use planning that put areas with high biodiversity and essential ecological processes in the territory at risk. It is the case of the ZEE, that has no legal support and make the planning process dependent on political decisions. In that sense, the change of government, functionaries, and regulations are the main causes of the unfinished materialization of the land-use plans (Madrigal-Martínez 2015).

Furthermore, we find some opportunities to improve the efforts on spatial conservation. Thus, the land declared as ANP is limited to 5% of the moist Puna and could be increased to, at best, 17% (by 2020, following the Aichi biodiversity targets (CBD 2010)). In the same way, the forestry zoning could be used in the moist Puna by its potential identifying areas that need special management due to their importance in providing ES. Finally, the process of managing ecosystems and their services could be facilitated through a common framework for the entire Peruvian territory, such as the classification of land-management units (Madrigal-Martínez 2014).

References

Abson, D.J., H. von Wehrden, S. Baumgärtner, J. Fischer, J. Hanspach, W. Härdtle, and H. Heinrichs et al. 2014. "Ecosystem Services as a Boundary Object for Sustainability." *Ecological Economics* 103: 29-37. doi:10.1016/j.ecolecon.2014.04.012.

Baraer, M., J.M. McKenzie, B.G. Mark, J. Bury, and S. Knox. 2009. "Characterizing Contributions of Glacier Melt and Groundwater during the Dry Season in a Poorly Gauged Catchment of the Cordillera Blanca (Peru)." *Advances in Geosciences* 22: 41-49. doi:10.5194/adgeo- 22-41-2009.

Blancas, Alexis Nicolás Ibáñez, María de los Ángeles La Torre-Cuadros, and Gleni Aracelly Mallma Carrera. 2018. "Using Foresight To Gain a Local Perspective on the Future of Ecosystem Services in a Mountain Protected Area in Peru." *Mountain Research and Development* 38 (3): 192-202. doi:10.1659/mrd-journal-d-17-00090.1.

Cochi Machaca, Nestor, Bruno Condori, Abel Rojas Pardo, Fabien Anthelme, Rosa Isela Meneses, Candace E Weeda, and Humberto L. Perotto- Baldivieso. 2018. "Effects of Grazing Pressure on Plant Species Composition and Water Presence on Bofedales in the Andes Mountain Range of Bolivia." *Mires Peat* 21 (15): 1-15. doi:10.19189/MaP.2017.OMB.303.

Convention on Biological Diversity. 2010. "*Aichi Biodiversity Targets*." Cbd.Int. http://www.cbd.int/sp/targets/.

Custodio, María, Fernán Chanamé, Samuel Pizarro, and Danny Cruz. 2018. "Quality of the Aquatic Environment and Diversity OF Benthic Macroinvertebrates of High Andean Wetlands of the Junín Region, Peru." *The Egyptian Journal of Aquatic Research* 44 (3): 195-202. doi:10.1016/j.ejar.2018.08.004.

de Valença, Anne W., Steven J. Vanek, Katherin Meza, Raul Ccanto, Edgar Olivera, Maria Scurrah, Egbert A. Lantinga, and Steven J. Fonte. 2017. "Land Use as a Driver of Soil Fertility and Biodiversity Across an Agricultural Landscape in the Central Peruvian Andes." *Ecological Applications* 27 (4): 1138-1154. doi:10.1002/eap.1508.

Duchicela, Sisimac A., Francisco Cuesta, Esteban Pinto, William D. Gosling, and Kenneth R. Young. 2019. "Indicators for Assessing Tropical Alpine Rehabilitation Practices." *Ecosphere* 10 (2): e02595. doi:10.1002/ecs2.2595.

Egarter Vigl, Lukas, Erich Tasser, Uta Schirpke, and Ulrike Tappeiner. 2017. "Using Land Use/Land Cover Trajectories to Uncover Ecosystem Service Patterns Across the Alps." *Regional Environmental Change* 17 (8): 2237-2250. doi:10.1007/s10113-017-1132-6.

Fjeldså, Jon. 2002. "Polylepis Forests-Vestiges of a Vanishing Ecosystem in the Andes." *Ecotropica*, no. 8: 111-123. https://www.researchgate.net/publication/285790471_Polylepis_forests-vestiges_of_a_vanishing_ecosystem_in_the_Andes

Fonte, Steven J., Steven J. Vanek, Pedro Oyarzun, Soroush Parsa, D. Carolina Quintero, Idupulapati M. Rao, and Patrick Lavelle. 2012. "Pathways to Agroecological Intensification of Soil Fertility Management by Smallholder Farmers in the Andean Highlands." *Advances in Agronomy Volume 116*, 125-184. doi:10.1016/b978-0-12-394277-7.00004-x.

Gibbon, Adam, Miles R. Silman, Yadvinder Malhi, Joshua B. Fisher, Patrick Meir, Michael Zimmermann, Greta C. Dargie, William R. Farfan, and Karina C. Garcia. 2010. "Ecosystem Carbon Storage Across the Grassland–Forest Transition in the High Andes of Manu National

Park, Peru." *Ecosystems* 13 (7): 1097-1111. doi:10. 1007/s10021-010-9376-8.

Grêt-Regamey, Adrienne, Sibyl Hanna Brunner, and Felix Kienast. 2012. "Mountain Ecosystem Services: Who Cares?" *Mountain Research and Development* 32 (S1): S23-S34. doi:10.1659/mrd-journal-d-10-00115.s1.

Haines-Young, R. and M.B. Potschin. 2018. "Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure". Available from www.cices.eu

Hartman, Brett D., Bodo Bookhagen, and Oliver A. Chadwick. 2016. "The Effects of Check Dams and Other Erosion Control Structures on the Restoration of Andean Bofedal Ecosystems." *Restoration Ecology* 24 (6): 761-772. doi:10.1111/rec.12402.

Hofstede, Robert G.M. 1995. "The Effects of Grazing and Burning on Soil and Plant Nutrient Concentrations in Colombian Páramo Grasslands." *Plant and Soil* 173 (1): 111-132. doi:10.1007/bf00155524.

Jameson, Joanne S., and Paul M. Ramsay. 2007. "Changes in High-Altitude Polylepis Forest Cover and Quality in the Cordillera De Vilcanota, Perú, 1956–2005." *Biological Conservation* 138 (1-2): 38-46. doi:10.1016/j.biocon.2007.04.008.

Josse, Carmen, Francisco Cuesta, Gonzalo Navarro, Edersson Cabrera, Eulogio Chacón Moreno, Wanderley Ferreira, Manuel Peralvo, José Saito, and Antonio Tovar. 2009. "*Ecosistemas De Los Andes Del Norte Y Centro*." Lima: Secretaría General de la Comunidad Andina. http://www.saber.ula.ve/handle/123456789/39336.

MA. 2005. "Ecosystems and Human Well-Being: Synthesis Report." Washington, D.C. http://www.islandpress.org.

Madrigal-Martínez, Santiago. 2014. "Tipología de Unidades de Síntesis Definidas por Criterios Ecológicos que Pueden Adoptarse en los Procesos de Meso Zonificación Ecológica Económica. Una Aproximación al Territorio Peruano." *Ecología Aplicada* 13 (1-2): 1. doi:10.21704/rea.v13i1-2.449.

Madrigal-Martínez, Santiago. 2015. "Metodología para la Evaluación y Actualización Participativa del Plan de Ordenamiento Territorial: El Caso De La Provincia De Tocache, San Martín (Perú)." *Ciudad y Territorio Estudios Territoriales* 47 (183): 107-119. https://recyt.fecyt.es/index.php/CyTET/article/view/76397/46746

Madrigal-Martínez, Santiago, and José Luis Miralles i García. 2019a. "Land- Change Dynamics and Ecosystem Service Trends Across the Central High-Andean Puna." *Scientific Reports* 9 (1). doi:10.1038/ s41598-019- 46205-9.

Madrigal-Martínez, Santiago, and José Luis Miralles i García. 2019b. "Understanding Land Use Changes in the Central High-Andean Moist Puna." *WIT Transactions on Ecology and the Environment* 238: 175-186. doi: 10.2495/SC190161

Maldonado Fonkén, M.S. 2014. "An Introduction to the Bofedales of the Peruvian High Andes." *Mires Peat* 15 (15): 1-13. http://mires-and-peat.net/media/map15/map_15_05.pdf

Mark, Bryan G., and Geoffrey O. Seltzer. 2003. "Tropical Glacier Meltwater Contribution to Stream Discharge: A Case Study in the Cordillera Blanca, Peru." *Journal of Glaciology* 49 (165): 271-281. doi:10.3189/172756503781830746.

Ministry of Economy and Treasury. 2019. "Banco de Inversiones." Lima. http://invierte.pe.

Ministry of Environment and SERNANP. 2016. "*Áreas Naturales Protegidas Del Perú Conservación Para El Desarrollo Sostenible*." Lima.

Ministry of Environment. 2017. "*Estado Situacional De La Zonificación Ecológica Y Económica (ZEE) a Nivel Regional*." Lima.

Ministry of Environment. 2014. "*La Estrategia Nacional De Diversidad Biológica Al 2021 Y Su Plan De Acción 2014- 2018*." Lima.

Ministry of Environment. 2019. "*Mecanismos de retibucion por servicios ecosistemicos*." Lima. http://serviciosecosistemicos.minam.gob.pe/

Ministry of Environment. 2015. "Mapa Nacional De Cobertura Vegetal - Memoria Descriptiva." Lima: Ministry of Environment. http://www.minam.gob.pe/patrimonio-natural/wp-content/uploads/sites/6/2013/10/MAPA-NACIONAL-DE-COBERTURA-VEGETAL-FINAL.compressed.pdf.

Oliveras, I, C Girardin, C E Doughty, N Cahuana, C E Arenas, V Oliver, W Huaraca Huasco, and Y Malhi. 2014. "Andean Grasslands Are As Productive As Tropical Cloud Forests." *Environmental Research Letters* 9 (11): 115011. doi:10.1088/1748-9326/9/11/115011.

Oscanoa, Luis, and Enrique Flores. 2016. "Influencia de Técnicas de Mejora de Suelos Sobre la Función Hídrica de Pastos Naturales Altoandinos." *Ecología Aplicada* 15 (2): 91-99. http://revistas.lamolina.edu.pe/index.php/eau/article/view/748/769.

Rodríguez, Luis C., Unai Pascual, and Hermann M. Niemeyer. 2006. "Local Identification and Valuation of Ecosystem Goods and Services from Opuntia Scrublands of Ayacucho, Peru." *Ecological Economics* 57 (1): 30-44. doi:10.1016/j.ecolecon.2005.03.022.

Rolando, Jose L., Jose C. Dubeux, Wendy Perez, David A. Ramirez, Cecilia Turin, Martín Ruiz-Moreno, Nicholas B. Comerford, Victor Mares, Sady Garcia, and Roberto Quiroz. 2017. "Soil Organic Carbon Stocks and Fractionation Under Different Land Uses in the Peruvian High-Andean Puna." *Geoderma* 307: 65-72. doi:10.1016/j.geoderma.2017.07.037.

Salvador, F., Jorge Monerris, and Line Rochefort. 2014. "Peatlands of the Peruvian Puna Ecoregion: Types, Characteristics and Disturbance." *Mires Peat* 15 (3): 1-17. http://mires-and-peat.net/pages/volumes/map15/map1503.php

Segnini, Aline, Adolfo Posadas, Roberto Quiroz, Débora Marcondes Bastos Pereira Milori, Sérgio Costa Saab, Ladislau Martin Neto, and Carlos Manoel Pedro Vaz. 2010. "Spectroscopic Assessment of Soil Organic Matter in Wetlands From the High Andes." *Soil Science Society of America Journal* 74 (6): 2246-2253. doi:10.2136/sssaj2009.0445.

SERFOR. 2019. "Plataforma de seguimiento de la Zonificación Forestal (v1.1)." Lima. https://datastudio.google.com/u/0/reporting/1rBWIgdSv6bguI4RaAyMnp nW9myR3t-sB/page/qCMh.

SERNANP. 2019. "Áreas Naturales Protegidas De Administración Nacional Con Categoria Definitiva." Lima.

Skarbø, Kristine, and Kristin VanderMolen. 2016. "Maize Migration: Key Crop Expands To Higher Altitudes under Climate Change in the Andes." *Climate and Development* 8 (3): 245-255. doi:10.1080/17565529.2015.1034234.

Sun, Feixiang, Yihe Lyu, Bojie Fu, and Jian Hu. 2016. "Hydrological Services by Mountain Ecosystems in Qilian Mountain of China: A Review." *Chinese Geographical Science* 26 (2):

174-187. doi:10.1007/s11769-015-0791-9.

Vásquez, Ekatherina, Brenton Ladd, and Nils Borchard. 2014. “Carbon Storage in a High-Altitude Polylepis Woodland in the Peruvian Andes.” *Alpine Botany* 124 (1): 71-75. doi:10.1007/s00035-014-0126-y.

Vuille, Mathias, Bernard Francou, Patrick Wagnon, Irmgard Juen, Georg Kaser, Bryan G. Mark, and Raymond S. Bradley. 2008. “Climate Change and Tropical Andean Glaciers: Past, Present and Future.” *Earth-Science Reviews* 89 (3-4): 79-96. doi:10.1016/j.earscirev.2008.04.002.

Young, Kenneth R. 2009. “Andean Land Use and Biodiversity: Humanized Landscapes in a Time of Change.” *Annals of the Missouri Botanical Garden* 96 (3): 492-507. doi:http://dx.doi.org/10.3417/2008035.

Zimmermann, Michael, Patrick Meir, Miles R. Silman, Anna Fedders, Adam Gibbon, Yadvinder Malhi, and Dunia H. Urrego et al. 2010. “No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes.” *Ecosystems* 13 (1): 62-74. doi:10.1007/s10021-009-9300-2.

APPENDIX II. SUPPLEMENTARY DATA

Table A1: List of land use/cover datasets used in the study.

Time-step	Map	Description	Type	Source
2000	High-Andean ecosystems (Josse, Cuesta, Navarro, Barrena, Cabrera, E, et al., 2009b)	Derived from at: 1: 250,000-scale forestry map of Peru (National Institute of Natural Resources, 2000), 30 Landsat TM images, and bio-climatic indexes (1 Km).	vector	2009, General Secretary of the Andean Community
2009	Flora cover (Ministry of Environment, 2012)	Scale at 1: 100,000, generated from 69 Landsat 5 (TM) images; with a minimum mapping area of 25 ha and, exceptionally, 5 ha in special cases.	vector	2012, Ministry of Environment of Peru
2013	Flora cover (Ministry of Environment, 2015a)	Scale at 1: 100,000, generated from 43 Landsat 5 (TM) images, RapidEye and Google Earth images for Andean land covers; with a minimum mapping area of 16 ha and, exceptionally, 5 ha in special cases.	vector	2015, Ministry of Environment of Peru

Table A2: Respondent pool particulars.

Id	Career	Discipline	Grade	Expert affiliation	Expert Country
1	Forestry	Natural Resource Management	Master	Agricultural National University of La Molina (UNALM)	Peru
2	Biology	Ecology	Master	UNALM	Peru
3	Forestry	Natural Resource Management	Doctor	UNALM	Peru
4	Physics	Ecosystem Services	Doctor	Water Competences Centre (CCA)	Peru
5	Forestry	Ecosystem Services	Doctor	Centre for International Forestry Research (CIFOR)	France
6	Agricultural	Hydrology	Master	The mountain institute (TMI)	Peru
7	Biology	Ecology	Doctor	UNALM	Peru
8	Zootechnics	Agostology	Doctor	UNALM	Peru
9	Biology	Landscape Ecology	Master	International Potato Centre (CIP)	Peru
10	Biology	Biogeography	Doctor	Research on Arid Zones Centre (CIZA)	Peru
11	Agricultural	Water Treatment	Master	UNALM	Peru
12	Agricultural	Hydrology	Master	UNALM	Peru
13	Agricultural	Hydrology and Climate Change	Doctor	National Institute in Agricultural Innovation (INIA)	Peru
14	Biology	Natural Resource Management	Doctor	TMI	Peru
15	Biology	Environmental Sciences	Doctor	Peruvian University Cayetano Heredia (UPCH)	Peru
16	Agricultural	Hydrology	Doctor	UNALM	Peru
17	Agronomy	Soil Sciences	Doctor	UNALM	Peru
18	Biology	Agostology	Doctor	UNALM	Peru
19	Biology	Climate Change	Master	University of Toronto	Peru
20	Biology	Biogeography	Doctor	Kew Gardens	Peru
21	Biology	Natural Resource Management	Doctor	Pontifical University Catholic of Peru (PUCP)	Peru
22	Agricultural	Hydrology and Climate Change	Doctor	National Service of Meteorology and Hydrology of Peru (SENAMHI)	Peru
23	Geography	Environmental Sciences	Master	Development Andean ecoregion Consortium (CONDESAN)	Ecuador
24	Civil	Water Resources	Doctor	Independent Consultant	Peru
25	Agronomy	Natural Resources and Climate Change	Master	TMI	France
26	Geography	Biogeography	Doctor	University of Texas	USA
27	Agricultural	Hydrology	Master	National Superintendence of Sewage Services of Peru (SUNASS)	Peru
28	Agronomy	Soil Sciences	Master	Environmental Ministry of Peru (MINAM)	Peru
29	Biology	Biogeography	Master	UNALM	Peru
30	Forestry	Hydrology and Climate Change	Master	UNALM	Peru

31	Agronomy	Soil Sciences	Master	UNALM	Peru
32	Meteorology	Meteorology and Water Sciences	Master	UNALM	Peru
33	History	Biogeography and Political Ecology	Master	University of Texas	USA
34	Biology	Ecosystem Services	Graduate	Nature and Culture International (NCI)	Peru
35	Economy	Environmental Sciences	Graduate	Institute for the Promotion of Water Management (IPROGA)	Peru
36	Biology	Ecology	Master	Major National University of San Marcos (UNMSM)	Peru
37	Forestry	Natural Resource Management	Master	Research National Institute of Glaciers and Mountain Ecosystems (INAIGEM)	Peru
38	Anthropology	Natural Resources and Climate Change	Doctor	TMI	Peru
39	Biology	Ecology	Master	UNALM	Peru
40	Biology	Ecology	Master	University of Quebec	Spain
41	Civil	Hydrology	Master	Imperial College London	Ecuador
42	Civil	Hydrology	Doctor	University of Cuenca	Ecuador
43	Civil	Hydrology	Doctor	University of Cuenca	Ecuador

Table A3. (A) Number of contributing experts for each LULC/regulating ES pairs, (B) Number of outliers, and (C) Number of experts accounted for scoring average. WP= water purification, RSE= regulation of soil erosion, WFR= water flow regulation, SQ= soil quality, GCR= global climate regulation.

		(A)					(B)					(C)				
CLC Code	LULC Unit	**WP**	**RSE**	**WFR**	**SQ**	**GCR**	**WP**	**RSE**	**WFR**	**SQ**	**GCR**	**WP**	**RSE**	**WFR**	**SQ**	**GCR**
1.1.1.	Continuous urban fabric	43	43	43	43	43	4	0	5	7	6	39	43	38	36	37
2.	Agricultural areas	43	43	42	42	42	1	0	2	0	0	42	43	40	42	42
3.1.1.	Low forest	41	42	42	42	42	2	3	1	2	1	39	39	41	40	41
3.2.	Forest plantations	40	41	41	42	40	0	3	0	6	3	40	38	41	36	37
3.3.1.	Natural grasslands	42	43	43	43	43	4	19	1	0	2	38	24	42	43	41
3.3.2.	Shrub lands	41	41	41	41	41	3	2	1	1	3	38	39	40	40	38
3.4.3.	Sparsely vegetated areas	42	42	42	42	41	2	2	2	4	3	40	40	40	38	38
3.4.5.	Glaciers	41	41	43	41	41	0	0	2	5	0	41	41	41	36	41
4.1.2.	Peatbogs and high-Andean wetlands	43	43	43	43	43	2	0	0	1	1	41	43	43	42	42
5.1.1.	Water courses	40	41	41	41	39	0	0	0	0	0	40	41	41	41	39
5.1.2.	Water bodies	42	42	43	42	42	7	0	4	0	0	35	42	39	42	42

Table A4. Provisioning ecosystem services assessed for the years 2000 and 2013 across the study area. Selected indicators, calculation method and source.

Ecosystem service	Indicators	Calculation method	Source
Crops	Productive potential associated to classes within the model of main capacity of soils (scale from 0 to 3);	Sum of normalised areas (Scale from 0 to 5) with Class (A) land suitable for annual crops and class (C) land suitable for permanent crops	• Ecological Economic Zoning of Ayacucho, Regional ordinance N°003-2013-GRA/CR • Ecological Economic Zoning of Huancavelica, Regional ordinance N°257-GOB.REG-HUANCAVELICA/CR • Ecological Economic Zoning of Junín, Regional ordinance N°218-2015-GRJ/CR.
Livestock	Productive potential associated to classes within the model of main capacity of soils (scale from 0 to 3);	Sum of normalised areas (Scale from 0 to 5) with Class (A) land suitable for annual crops, class (C) land suitable for permanent crops and class (P) land suitable for grazing.	

Figure A5. ES scaling method.

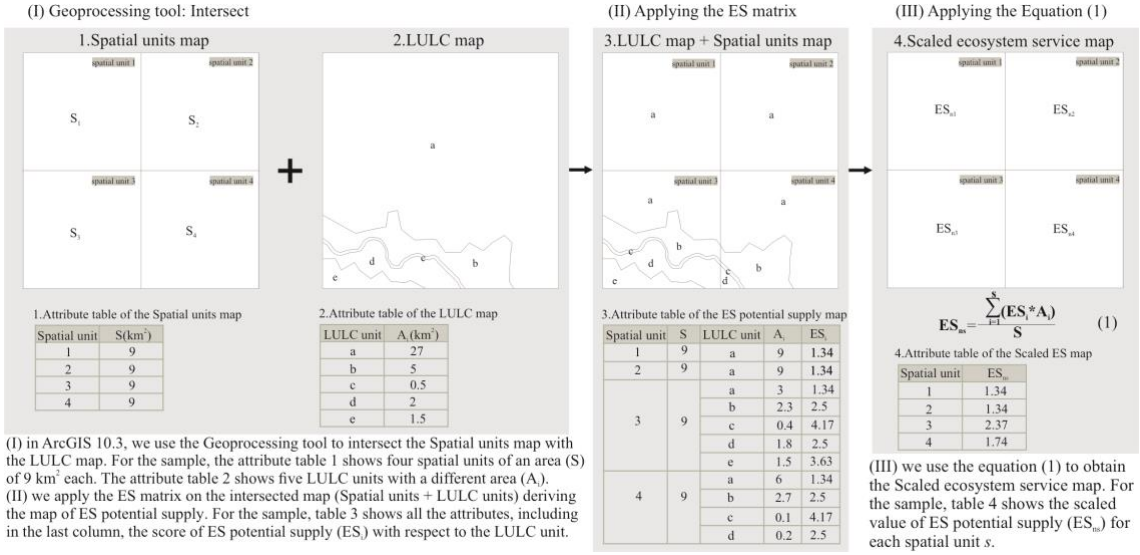

Table A6. ES matrix (2009) of the scenario created for the sensitivity analysis

CLC Code	Regulating ES					Provisioning ES	
	Water purification	Regulation of soil erosion	Water flow regulation	Soil quality	Global climate regulation	Crops	Livestock
1.1.1.	0.18	1.21	0.32	0.00	0.00	0.00	0.00
2.	1.50	2.74	3.55	3.16	2.00	2.93	3.51
3.1.1.	2.79	3.43	3.37	3.23	3.42	0.66	1.03
3.2.	2.71	4.53	3.85	3.59	4.79	1.54	2.03
3.3.1.	2.65	3.10	2.86	2.80	2.47	2.39	3.08
3.3.2.	2.55	3.02	2.93	2.90	2.78	2.43	2.63
3.4.3.	0.75	0.50	0.75	0.68	0.61	1.20	1.58
3.4.5.	0.00	0.00	3.66	0.00	0.76	0.00	0.00
4.1.2.	3.64	3.01	3.43	4.29	3.65	3.00	4.39
5.1.1.	4.18	0.00	4.02	0.00	0.00	0.00	0.00
5.1.2.	4.65	0.00	5	0.00	0.00	0.00	0.00

CLC code: 1.1.1. Continuous urban fabric; 2. Agricultural areas; 3.1.1. Low forest; 3.2. Forest plantations; 3.3.1. Natural grasslands; 3.3.2. Shrublands; 3.4.3. Sparsely vegetated areas; 3.4.5. Glaciers; 4.1.2. Peatbogs and high-Andean wetlands; 5.1.1. Water courses; 5.1.2. Water bodies.

Table A7. ES matrix (2013) of the scenario created for the sensitivity analysis

CLC Code	Regulating ES					Provisioning ES	
	Water purification	Regulation of soil erosion	Water flow regulation	Soil quality	Global climate regulation	Crops	Livestock
1.1.1.	0.18	1.21	0.32	0.00	0.00	0.00	0.00
2.	1.50	3.14	3.95	3.56	2.00	3.33	3.91
3.1.1.	2.39	3.03	2.97	2.83	3.02	0.26	0.63
3.2.	2.71	4.93	4.25	3.99	5	1.54	2.03
3.3.1.	2.25	2.70	2.46	2.40	2.07	2.79	3.48
3.3.2.	2.15	2.62	2.53	2.50	2.38	2.83	3.03
3.4.3.	0.75	0.50	0.75	0.68	0.61	1.20	1.58
3.4.5.	0.00	0.00	3.26	0.00	0.36	0.00	0.00
4.1.2.	3.24	2.61	3.03	4.29	3.25	3.40	4.79
5.1.1.	4.58	0.00	4.42	0.00	0.00	0.00	0.00
5.1.2.	5	0.00	5	0.00	0.00	0.00	0.00

CLC code: 1.1.1. Continuous urban fabric; 2. Agricultural areas; 3.1.1. Low forest; 3.2. Forest plantations; 3.3.1. Natural grasslands; 3.3.2. Shrublands; 3.4.3. Sparsely vegetated areas; 3.4.5. Glaciers; 4.1.2. Peatbogs and high-Andean wetlands; 5.1.1. Water courses; 5.1.2. Water bodies.

Figure A8. Web diagrams showing the changes that provinces followed from one cluster to another during the time period: (A) Land-change dynamic clusters; (B) Bundles of ES trends; (C) Links between land-change dynamic clusters and bundles of ES trends.

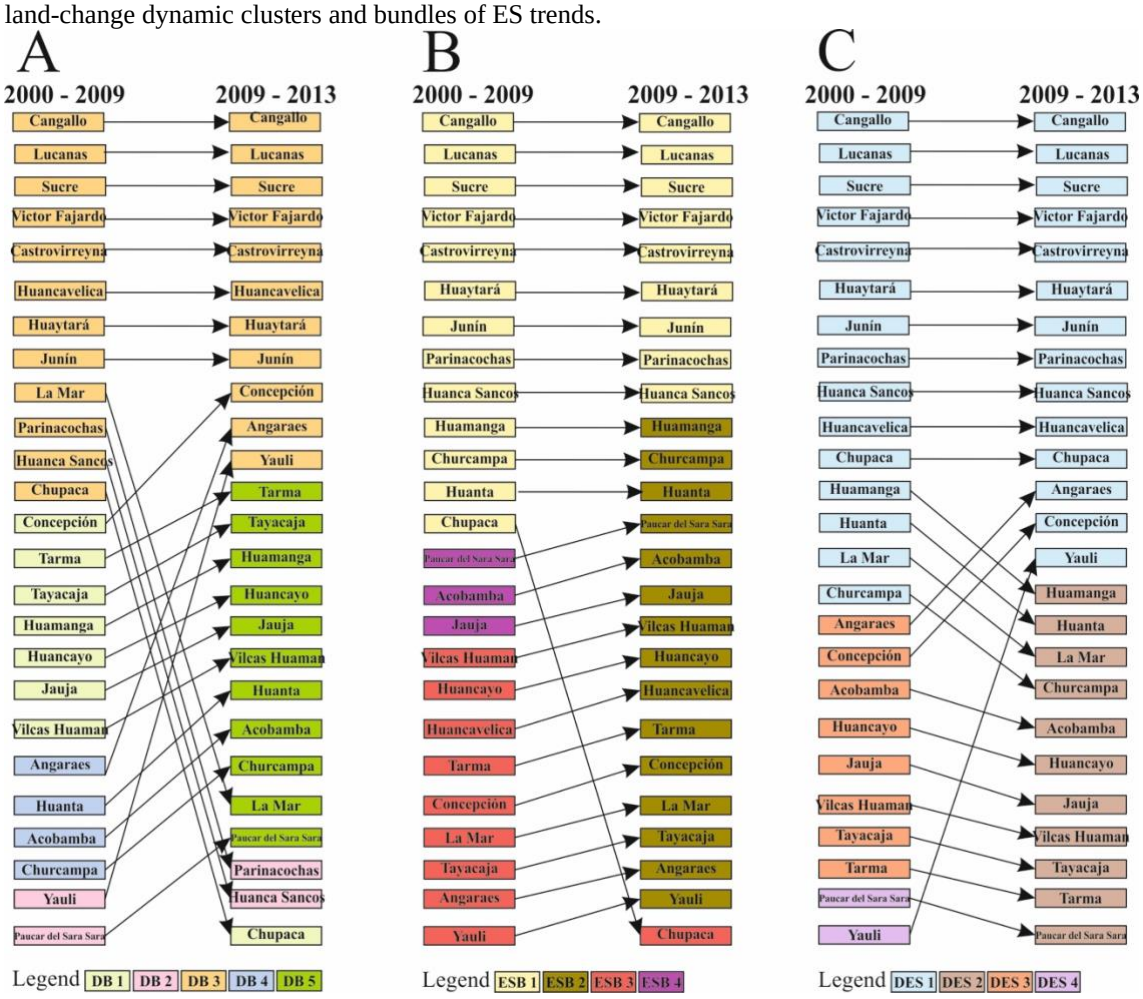

Table A9. Pairwise Spearman's rank correlation between trends of ES for the two-time periods.

Ecosystem service pair	2000-2009	R	Strength	2000-2013	R	Strength
Regulating						
Water purification and Regulation of soil erosion	0.99	S*	H	0.93	S*	H
Water purification and Water flow regulation	0.92	S*	H	0.93	S*	H
Water purification and Soil quality	0.80	S*	H	0.96	S*	H
Water purification and Global climate regulation	0.97	S*	H	0.94	S*	H
Regulation of soil erosion and Water flow regulation	0.91	S*	H	0.87	S*	H
Regulation of soil erosion and Soil quality	0.83	S*	H	0.91	S*	H
Regulation of soil erosion and Global climate regulation	0.97	S*	H	0.86	S*	H
Water flow regulation and Soil quality	0.58	S*	H	0.89	S*	H
Water flow regulation and Global climate regulation	0.93	S*	H	0.94	S*	H
Soil quality and Global climate regulation	0.79	S*	H	0.97	S*	H
Regulating and Provisioning						
Water purification and Crops	-0.89	T*	H	-0.72	T*	H
Water purification and Livestock	-0.71	T*	H	-0.52	T*	H
Regulation of soil erosion and Crops	-0.86	T*	H	-0.86	T*	H
Regulation of soil erosion and Livestock	-0.66	T*	H	-0.67	T*	H

Water flow regulation and Crops	-0.92	T*	H	-0.75	T*	H
Water flow regulation and Livestock	-0.78	T*	H	-0.63	T*	H
Soil quality and Crops	-0.51	T*	H	-0.65	T*	H
Soil quality and Livestock	-0.28	T	W	-0.50	T*	H
Global climate regulation and Crops	-0.83	T*	H	-0.62	T*	H
Global climate regulation and Livestock	-0.62	T*	H	-0.52	T*	H
Provisioning						
Crops and Livestock	0.89	S*	H	0.87	S*	H

Relationship (R): synergies (S) and trade-offs (T). *Significant at a $p < 0.05$. Scale of correlation strength: high (H) $-0.5 \leq r \geq 0.5$, moderate (M) $-0.3 \leq r \geq 0.3$, weak (W) $-0.1 < r > 0.1$

Table A10. Results of RDA analysis between land-change dynamics and ES trends for the two-time periods.

Model T1 (2000 – 2009)	Model T2 (2009 – 2013)
Df AIC F Pr(>F) - D2 1 -142.172 3.8336 0.065 . - D3 1 -137.912 8.2607 0.010 ** - D6 1 -107.009 77.2811 0.005 ** - D1 1 -82.949 234.6823 0.005 ** - D4 0 -144.556 -Inf --- Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 Inertia Proportion Rank Total 0.042621 1.000000 Constrained 0.040470 0.949512 4 Unconstrained 0.002152 0.050488 7 Inertia is variance	Df AIC F Pr(>F) - D6 1 -142.69 4.1895 0.055 . - D1 1 -125.64 28.8284 0.005 ** - D2 1 -76.80 330.4457 0.005 ** --- Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 Inertia Proportion Rank Total 0.048142 1.000000 Constrained 0.045874 0.952883 3 Unconstrained 0.002268 0.047117 7 Inertia is variance

Figure A11. Spatial distribution of each driver for both time periods (distance from Lima stay invariable for both periods). The values of drivers are organised in equal interval quintiles.

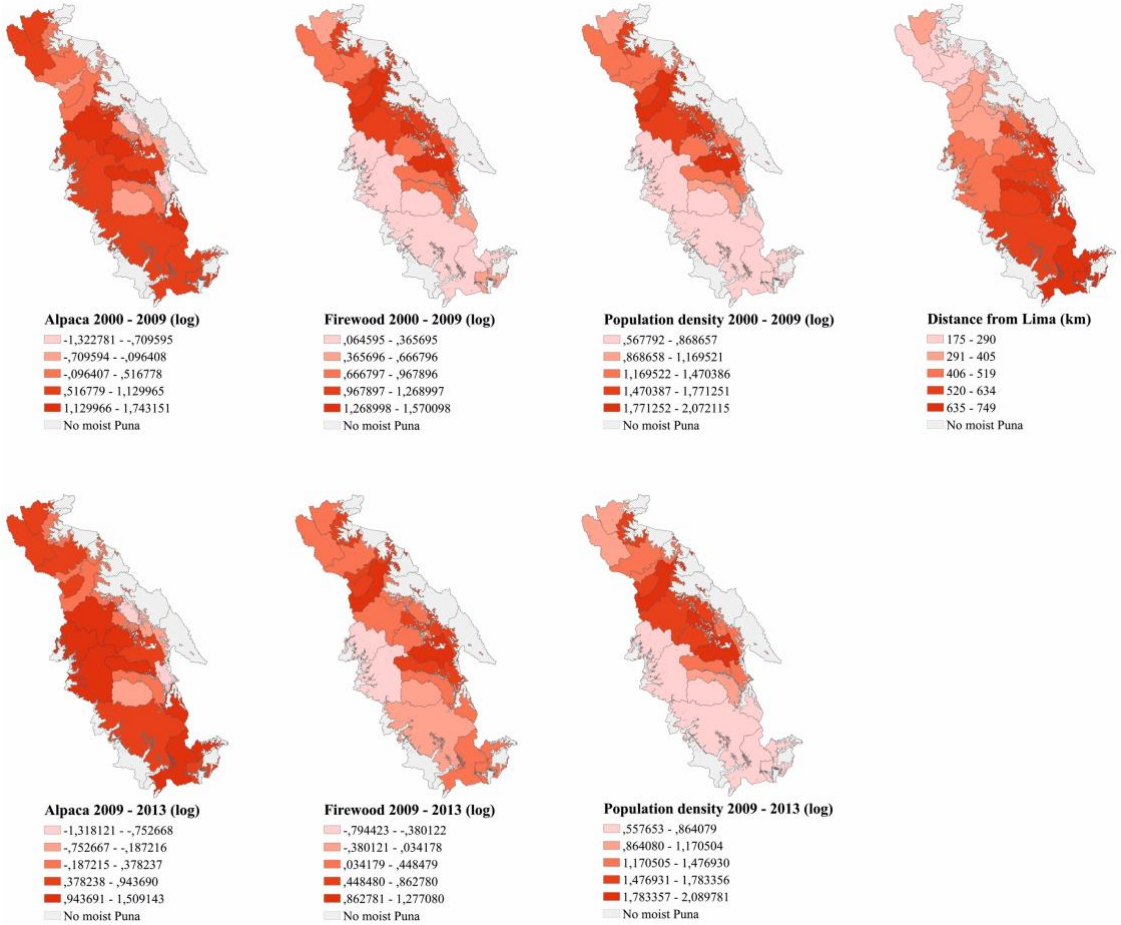

Table A12. Area and percentage of change of bundles generated with ES values at each spatial scale over time.

Scale	Transition id	Year 2000	2009	2013	Area (Km^2)	%
Provincial	1	B1	B1	B1	836	3.03
	2	B1	B1	B2	3431	12.43
	3	B2	B1	B1	4560	16.51
	4	B2	B1	B2	2734	9.90
	5	B2	B2	B2	2814	10.19
	6	B3	B2	B2	4183	15.15
	7	B3	B3	B2	1130	4.09
	8	B3	B3	B3	7924	28.70
Municipal	1	B1	B1	B1	402	1.46
	2	B1	B1	B2	180	0.65
	3	B2	B1	B1	225	0.82
	4	B2	B1	B2	292	1.06
	5	B2	B2	B1	247	0.90
	6	B2	B2	B2	3875	14.03
	7	B2	B2	B3	1185	4.29
	8	B3	B1	B1	61	0.22
	9	B3	B1	B2	40	0.14
	10	B3	B2	B1	12	0.04
	11	B3	B2	B2	1879	6.81
	12	B3	B2	B3	1423	5.15
	13	B3	B3	B2	810	2.93

	14	B3	B3	B3	16979	61.49
Coarse-grid	1	B1	B1	B1	3249	11.96
	2	B1	B1	B2	675	2.48
	3	B1	B1	B3	162	0.60
	4	B1	B2	B1	9	0.03
	5	B1	B2	B2	81	0.30
	6	B1	B2	B3	36	0.13
	7	B2	B1	B1	684	2.52
	8	B2	B1	B2	225	0.83
	9	B2	B1	B3	9	0.03
	10	B2	B2	B1	180	0.66
	11	B2	B2	B2	2403	8.84
	12	B2	B2	B3	225	0.83
	13	B2	B3	B2	18	0.07
	14	B2	B3	B3	126	0.46
	15	B3	B1	B1	297	1.09
	16	B3	B1	B2	162	0.60
	17	B3	B1	B3	108	0.40
	18	B3	B2	B1	72	0.26
	19	B3	B2	B2	1179	4.34
	20	B3	B2	B3	414	1.52
	21	B3	B3	B1	45	0.17
	22	B3	B3	B2	450	1.66
	23	B3	B3	B3	16362	60.22
Fine-grid	1	B1	B3	B3	1	0.00
	2	B1	B2	B2	4	0.01
	3	B1	B2	B1	0.3	0.00
	4	B1	B1	B3	4	0.01
	5	B1	B1	B2	30	0.11
	6	B1	B1	B1	1014	3.67
	7	B2	B3	B3	180	0.65
	8	B2	B3	B2	3	0.01
	9	B2	B2	B3	817	2.96
	10	B2	B2	B2	3022	10.95
	11	B2	B2	B1	25	0.09
	12	B2	B1	B2	4	0.01
	13	B2	B1	B1	41	0.15
	14	B3	B3	B3	19985	72.45
	15	B3	B3	B2	476	1.73
	16	B3	B3	B1	24	0.09
	17	B3	B2	B3	435	1.58
	18	B3	B2	B2	1510	5.47
	19	B3	B2	B1	6	0.02
	20	B3	B1	B1	7	0.03

Table A13. Area and percentage of change of bundles generated with ES values of the sensitivity analysis at each spatial scale over time.

Spatial scale	Transition id	2000	2009	2013	Area (km^2)	%
Provincial	1	3	2	1	27621.41	100%
Municipal	1	1	2	2	1259.83	5%
	2	1	1	2	30.00	0%
	3	1	1	1	125.59	0%
	4	3	2	2	22982.92	83%
	5	3	2	1	16.92	0%
	6	3	1	2	78.10	0%
	7	3	1	1	3118.98	11%
Coarse-grid	1	1	1	1	1458	5%
	2	1	1	2	36	0%

	3	1	2	1	9	0%
	4	1	2	2	3357	12%
	5	1	3	2	27	0%
	6	2	1	1	54	0%
	7	2	2	1	18	0%
	8	2	2	2	1107	4%
	9	2	3	2	9	0%
	10	3	1	1	270	1%
	11	3	2	1	108	0%
	12	3	2	2	20511	75%
	13	3	2	3	9	0%
	14	3	3	1	9	0%
	15	3	3	2	171	1%
	16	3	3	3	18	0%
Fine-grid	1	1	1	1	1115.75	4%
	2	1	1	2	22.25	0%
	3	1	2	1	2.75	0%
	4	1	2	2	265.5	1%
	5	1	3	1	1.5	0%
	6	1	3	2	2.5	0%
	7	1	3	3	2	0%
	8	2	1	1	57.75	0%
	9	2	1	2	0.5	0%
	10	2	2	1	31.25	0%
	11	2	2	2	3496.75	13%
	12	2	2	3	0.5	0%
	13	2	3	2	10.75	0%
	14	2	3	3	17	0%
	15	3	1	1	129	0%
	16	3	1	2	17.25	0%
	17	3	2	1	51.25	0%
	18	3	2	2	21955.75	80%
	19	3	2	3	6.5	0%
	20	3	3	1	2.75	0%
	21	3	3	2	266.75	1%
	22	3	3	3	129.75	0%

Table A14. Area and percentage of change of bundles resulting from ΔES values at each scale over time.

Scale	Transition id	Time-period		Area (Km^2)	%
		2000-2009	2009-2013		
Provincial	1	B1	B3	7756	28.09
	2	B1	B2	3196	11.58
	3	B2	B2	13229	47.91
	4	B2	B3	3431	12.43
Municipal	1	B1	B1	12	0.04
	2	B1	B2	2083	7.54
	3	B1	B3	1128	4.09
	4	B2	B2	20977	75.97
	5	B2	B3	3412	12.36
Coarse-grid	1	B1	B1	72	0.26
	2	B1	B2	1782	6.56
	3	B1	B3	693	2.55
	4	B2	B1	450	1.66
	5	B2	B2	22689	83.50
	6	B2	B3	1233	4.54
	7	B3	B2	189	0.70
	8	B3	B3	63	0.23
Fin	1	B1	B1	18	0.06

	2	B1	B2	1602	5.81
	3	B1	B3	435	1.58
	4	B2	B1	581	2.11
	5	B2	B2	23882	86.57
	6	B2	B3	883	3.20
	7	B3	B2	180	0.65
	8	B3	B3	6	0.02

Table A15. Area and percentage of change of bundles generated with ΔES values of the sensitivity analysis at each spatial scale during the two periods.

Spatial scale	Transition id	2000-2009	2009-2013	Area (km^2)	%
Provincial	1	2	3	7081.31	26%
	2	1	3	20531.11	74%
Municipal	1	1	1	2781.47	10%
	2	1	2	26.24	0%
	3	2	1	525.67	2%
	4	2	2	1041.59	4%
	5	3	2	242.93	1%
	6	3	1	22994.45	83%
Coarse-grid	1	1	1	1998	7%
	2	1	2	45	0%
	3	1	3	18	0%
	4	2	1	3150	12%
	5	2	2	1764	6%
	6	2	3	63	0%
	7	3	1	19314	71%
	8	3	2	765	3%
	9	3	3	54	0%
Fine-grid	1	1	1	1424.25	5%
	2	1	2	75	0%
	3	1	3	157.25	1%
	4	2	1	1535	6%
	5	2	2	2282	8%
	6	2	3	44.75	0%
	7	3	1	20258.5	73%
	8	3	2	1640.5	6%
	9	3	3	168.5	1%