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Putting the Ecosystem Services idea at work: Applications on impact assessment and territorial planning

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A R T I C L E I N F O

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A B S T R A C T

South America is experiencing profound land use and land cover changes. Their consequences on the Ecosystem Services (ES) supply and human well-being need to be diagnosed and monitored in order to support informed decisions both in management and territorial planning. The ES concept provides a key framework to evaluate human impacts on nature. The use of spatially explicit indicators able to characterize ES supply can turn operative the ES framework, enabling for sustainability assessment. The Ecosystem Services Supply Index (ESSI) is a synoptic indicator that estimates and maps supporting and regulating ES related to water and carbon dynamics from data provided by remote sensors of free access and wide spatial coverage. The ESSI merges two attributes of the Normalized Difference Vegetation Index (NDVI) annual dynamics: the annual average ($NDVI_{MEAN}$, a proxy of total C gains) and the intra-annual coefficient of variation ($NDVI_{CV}$, an indicator of seasonality). In this article we proposed two objectives: 1) to describe the conceptual foundation of the ESSI and to gather the empirical support that shows its ability to explain the spatial-temporal variation in different ES, and to present a new case of empirical ESSI assessment, and 2) to synthesize the contribution of the ESSI in socio ecosystem diagnosis, monitoring and territorial planning stages in 8 existing cases of application. We also explored the links to the decision-making process by diverse stakeholders including local research and development institutions, NGOs and government agents. Cases corresponded to a wide range of situations from humid and dry forests to grasslands, and from local to subcontinental scales in southern South America. We found that ESSI was successfully applied for diagnosis, planning and monitoring processes which helped to better define interventions in management decisions and also to empower the most vulnerable stakeholders under territorial and environmental conflicts.

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1. Introduction

South America is experiencing profound Land-Use and Land-Cover Changes (LULCC) processes (Eva et al., 2004; Volante et al., 2015; Ramankutty et al., 2018). In the last 50 years, in most countries of the world the population grew and the cultivated area per inhabitant remained constant or decreased (Rudel et al., 2009; FAOSTAT, 2019). In contrast, Argentina, Brazil, Bolivia, Paraguay and Uruguay are some of the few countries in the world where the cultivated area per inhabitant increased even when their population grew (FAOSTAT, 2019). This increase was due to the conversion of natural covers (forests and grasslands) into croplands, pastures or tree plantations. The Chaco and Cerrado Forest (that extend through Bolivia, Argentina, Paraguay, and Brazil) are some of the most threatened biomes, as their rates of deforestation are the largest in the world (Marris, 2005; Brannstrom et al., 2008; UMSEF, 2012; Hansen et al., 2013; Salazar et al., 2015). In both ecoregions, the proportion of natural vegetation transformed reached 34% and 52% of the historical area, respectively (Hansen et al., 2013; Salazar et al., 2015). In the Río de la Plata Grasslands (that extends through Argentina, Uruguay and Brazil) there is another focus of agricultural and tree plantations expansion with unprecedented replacement rates (Paruelo et al., 2006; Baldi and Paruelo, 2008; Vega et al., 2009). During the period 1990–2010, LULCC rates were higher than during the previous 20-year period and more than 15% of the grassland area was lost (Modernel et al., 2016; Baeza and Paruelo, 2020). As a result of those changes, more than 40% of the annual carbon (C) gains were appropriated by humans in the region (Baeza and Paruelo, 2018; Paruelo et al., 2019).

These changes generated both territorial and environmental conflicts. Since the beginning of 2000, land grabbing has gained importance in South America (Borras et al., 2012). This process implies that companies get access to land on a large scale to produce commodities for export (Borras et al., 2011). In many cases, land grabbing involves expelling aboriginal and peasants communities from their lands. In the Argentine Chaco, this process gave rise to numerous territorial disputes with a high level of social conflict (Seghezzo et al., 2011; REDAF, 2013; Aguiar et al., 2016). Furthermore, LULCC modify the structure and functioning of ecosystems (Chapin et al., 2002), being one of the main causes of global biodiversity loss (Sala et al., 2000) and climate change (Vitousek et al., 1997, Pielke Sr et al., 2002). Local evidences showed that LULCC have negative impacts on (C) gains dynamics (Volante et al., 2012; Baldi et al., 2013; Texeira et al., 2015), emission of greenhouse gases (Gasparri et al., 2008; Fearnside et al., 2009; Baccini et al., 2012; Harris et al., 2012; Houghton, 2012), water regulation (Nosetto et al., 2005; Amdan et al., 2013; Marchesini et al., 2017; Levy et al., 2018), landscape fragmentation (Baldi and Paruelo, 2008; Carvalho et al., 2009; Gasparri and Grau, 2009) and soil organic carbon content (Caride et al., 2012; Eclesia et al., 2012; Wantzen et al., 2012; Conti et al., 2014; Villarino et al., 2017; Osinaga et al., 2018). Then, LULCC compromise the supply of regulating and supporting Ecosystem Services (ES) such as the provision of clean water, flood prevention, or the maintenance of soil productive capacity, among others (Millenium Assessment, 2005; Fisher et al., 2009).

Given the consequences of LULCC on ES supply and human well-being, to diagnose and monitor the impacts of human activities is critical to make informed decisions, both in management and territorial planning. Land-use transitions, mainly the replacement of natural vegetation devoted to logging or extensive grazing by more intensive livestock production systems, crops or tree plantations, tend to a generalized intensification process (Foley et al., 2005). Land uses at the farm and landscape level are becoming less diverse in time and space, and more dependent on energy subsidies and external inputs (Bommarco et al., 2013). The social, economic, and environmental sustainability of this intensification is questioned with different emphasis. Some definitions of sustainability advanced to turn operative the concept, linking sustainability to ES supply (McCartney et al., 2014). The conformation of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) shows advances in transforming the concept of ES into a tool for the decision-making process and policy definition (i.e., Bateman et al., 2013; Paruelo and Laterra, 2019). For example, Wu (2013) defines landscape sustainability as the ability to consistently provide specific ES for the maintenance and improvement of human well-being over the long term. To the extent that the ES supply can be quantified, it is possible to advance in an operational definition of the level of the landscape's sustainability.

The ES concept provides a key framework for evaluating human impacts on nature and guiding environmental policies and territorial planning. As noted by different authors (Kremen, 2005; Wong et al., 2015; Costanza et al., 2017) the use of the ES concept in decision-making is still limited. Probably, the methodological challenges involved in characterizing and quantifying ES supply preclude a wider use of the concept. The use of spatially explicit indicators, to characterize the level of ES supply over time and space, is a key to making operative the ES concept and enabling sustainability assessment and territorial planning. Evidence on the association among ES may derive from their empirical correlations over a given region (i.e. Spake et al., 2017) or from the type and intensity of the association of different ES with indicators or proxies. For example, biodiversity of particular taxa has been used to indicate ES supply given its relationship with a variety of ES (de Groot et al., 2010). Also, land cover patterns were used as the basis of several systems that maps ES based on its relationship with land uses (i.e. InVEST, ECOSER). A key step for defining territorial planning scenarios is to empirically develop impact functions, where ES supply is a function of the level of human intervention (Paruelo and Dieguez, 2019). On the other hand, socially accepted ES indicators may provide the basis to monitor policy implementations over large areas at the landscape level. An interesting example in Uruguay is the evaluation of a key ES, the soil conservation. This ES is regularly quantified to evaluate soil management plans using a widely accepted model, the Universal Soil Loss Equation (USLE-RUSLE) (Wischmeier and Smith, 1978; Renard et al., 1997), adjusted to local conditions (Hill et al., 2008; García-Préchac et al., 2017).

The Ecosystem Services Supply Index (ESSI) is a synoptic indicator that estimates and maps supporting and regulating ES related to carbon and water dynamics (Paruelo et al., 2016). In this article we have two objectives. First, to describe the conceptual foundation of the ESSI and to gather the empirical support that shows its ability to explain the spatial-temporal variation in different ES, and to present a new case of empirical ESSI assessment. The second objective is to synthesize the contribution of the ESSI in socio ecosystem diagnosis, monitoring and territorial planning stages in 8 existing cases of application and their links to decision-making process by diverse stakeholders: 1) Assessment of the environmental situation of Argentina; 2) Assessment of the status of Atlantic Forest; 3)

Forest degradation assessment along grazing gradients in La Rioja, Argentina; 4) Forest strips contribution to ES supply at the landscape level in Semi-Arid Chaco forests; 5) Assessment of the effect of protected areas on the ES supply in Sierras del Este region, Uruguay; 6) A functional assessment of vegetation heterogeneity derived from livestock management in Uruguayan grasslands; 7) Environmental liabilities assessment caused by illegal deforestation for its use in legal trials in Salta, Argentina and 8) Grasslands conservation assessment in Centro-Sur region, Uruguay. These objectives are developed in sections 2 and 3 respectively and finally, in section 4, we discuss the implications, scopes, and limitations of the ESSI use for diagnosis, planning, and monitoring of socio-ecosystems.

2. Conceptual and empirical support of Ecosystem Services supply index (ESSI)

The ESSI was proposed by Paruelo et al. (2016) and it was originally named "Ecosystem Services Provision Index (ESPI)". From this work, the authors decided to replace "Provision" by "Supply" (and thus call it ESSI) since the idea of provision involves the capture of ES by different stakeholders. This not only depends on the patterns of propagation of the ES (supply), but also on the level of demand and access by the beneficiaries (Laterra et al., 2019), which are not necessarily coupled in time and space (Verón et al., 2011; Yahdjian et al., 2015; Laterra et al., 2016). The ESSI is a synoptic indicator that estimates and maps supporting and regulating ES related to carbon and water dynamics. It is based on vegetation indices derived from remote sensing data, which constitute robust estimators of Net Primary Productivity (NPP) (Monteith, 1972; Piñeiro et al., 2006), an integrating variable of ecosystem functioning (McNaughton et al., 1989). This represents an advantage, since it is possible to make estimations over large areas, with a low cost and based on the same observation protocol (Paruelo, 2008). In addition, the estimates can be based on satellite images provided by different sensors that offer a different spatial and temporal resolution. The ESSI merges two attributes of Normalized Difference Vegetation Index (NDVI) annual dynamics: the annual average ($NDVI_{MEAN}$, a proxy of total C gains) and the intra-annual coefficient of variation ($NDVI_{CV}$, an indicator of seasonality): $ESSI = NDVI_{MEAN} * (1 - NDVI_{CV})$. In such a way, those sites where annual productivity is higher and more seasonally stable would have a higher ES supply. The ESSI values range from 0 to 1 because the values of each functional attribute ($NDVI_{MEAN}$ and $NDVI_{CV}$) are normalized considering their highest and lowest values at a regional scale (for more details see Paruelo et al., 2016).

The foundation of the ESSI is based on both the conceptual framework of the ES cascade model and the ES bundles concept. The cascade model was originally proposed by Haines-Young and Potschin (2010) (Boyd and Banzhaf, 2007; Fisher and Turner, 2008; de Groot et al., 2010; Paruelo et al., 2016) and provides a solid conceptual framework to incorporate ES into decision-making. Such a model explicitly connects ecosystem functioning and structure with intermediate and final ES (Fisher et al., 2009) that determine social benefits. In this framework, intermediate ES (the ecosystem processes and structure as such) are dissociated from final ES (the processes that determine human benefits) (Boyd and Banzhaf, 2007; Fisher et al., 2009). The cascade model is compatible with the ES bundles concept, which involves sets of services that appear together repeatedly (Raudsepp-Hearne et al., 2010). Such associations result from similar responses of different ES to the same change driver or ecological process (Bennett et al., 2009). Likewise, intermediate ES (e.g. NPP, Evapotranspiration) determine the provision of a set of highly correlated final ES (e.g., C sequestration, water regulation) that are affected by the same stress or perturbation factors (e.g. deforestation, overgrazing, burning) (Haines-Young and Potschin, 2010). According to this scheme, the ESSI represents an integrative index of ecosystem functioning (in particular of NPP), which gives rise to the cascade and is capable of describing the variation in different regulating and supporting ES (some of them intermediate and others final ES) that vary together in the same direction (ES bundles).

The support for using ESSI as a proxy of ES supply was originally based on its positive relationship with four ES estimated from empirical data or mechanistic models: groundwater recharge and avian richness in Dry Chaco forests and soil organic carbon (SOC) and evapotranspiration in Río de la Plata Grasslands (Paruelo et al., 2016). These models showed that the ESSI was able to explain between 48 to 66% of the variability from these four ES (Table 1). The ESSI trends were mapped for the period 2000–2014 with a spatial resolution of 1 km in both ecoregions (Paruelo et al., 2016). About one-third of the area showed significant trends (32.4%), most of which were negative (30.2%), which meant a generalized decrease in ES supply.

Recently, the empirical evaluation of the ESSI was expanded to two additional ES (Table 1). The first additional evaluation corresponded to an assessment of the ESSI as an indicator of avian richness in agroecosystems of the Argentine Pampas (Weyland et al.,

Table 1
Summary of the 5 existing ESSI evaluation cases in the literature and the new empirical ESSI evaluation case (Fig. 1) presented in this article. Each case is described according to the Final ES evaluated, the region in which it was evaluated, the type of statistical model applied (linear with positive slope or non-linear), the explanatory ability of the ESSI and the corresponding reference.

ES supply evaluated	Region of study area	Type of statistic model applied	Proportion of the variance explained by ESSI (R^2)	Reference
Groundwater recharge	Dry Chaco forests	Simple linear regression (+)	0.645	Paruelo et al. (2016)
Evapotranspi-ration	Río de la Plata grasslands	Non-linear -Generalized additive model	0.529	Paruelo et al. (2016)
Avian richness	Dry Chaco forests	Non-linear -Generalized additive model	0.484	Paruelo et al. (2016)
Avian richness	Río de la Plata grasslands	Simple linear regression (+)	0.456	Weyland et al. (2019)
Soil Organic Carbon	Río de la Plata grasslands	Non-linear -Generalized additive model	0.662	Paruelo et al. (2016)
Soil Organic Carbon	Dry Chaco forests	Simple linear regression (+)	0.679	Fig. 1

2019). The relationship was positive at both local and landscape scales for different environmental conditions (dry and normal precipitations years). ESSI explained the highest percent of the variability (46%) in avian richness at the landscape scale (64 km^2). The second evaluation corresponded to the relationship between the ESSI and the soil organic carbon (SOC) content in Dry Chaco forests ecoregion. Field studies showed that SOC decrease following the conversion from native forest into crops or pastures (Villarino et al., 2017; Baldassini and Paruelo, 2020). Moreover, modeling analysis showed that these changes were mainly determined by decreases in incoming inputs (C gains) than by reductions in outputs (erosion and soil respiration) (Baldassini and Paruelo, 2020). Using the empirical field data measured by Baldassini and Paruelo (2020) in 30 sites including 13 croplands, 7 pastures and 10 patches of native forest, we evaluated if ESSI was able to explain the variation in SOC in the upper 20 cm of the soil layer following conversion. For each sampling site, we obtained the ESSI mean for the period 2000–2015 (Paruelo et al., 2016). Sites with crops and pastures showed lower ESSI mean values than forests and close to 68% of the spatial variation in SOC was explained by the ESSI (Fig. 1). These results indicate that ESSI provide the basis to spatially generalize C stocks inventories over a large region that experience profound changes in land cover.

3. Cases of ESSI applications and their links with decision-making

Based on the existing empirical evaluation (developed in section 2), which shows that the ESSI is a proxy for several ES that vary together (ES bundles), we compiled 8 cases where the ESSI was applied as an integrative index of the level of ES supply to make diagnoses, evaluate land use alternatives or policies or define monitoring schemes (Table 2, Fig. 2). The cases corresponded to a wide range of socio-ecological systems in southern South America. The ESSI was applied in arid, semiarid and humid forests as well as in temperate grasslands areas. The scale ranged from local (e.g. case 3, at farm level) to subcontinental (e.g. case 2, at ecoregion level). Most of the applications of ESSI were oriented to provide a quantitative diagnosis over an area subjected to land cover transformation (e.g. cases 1, 2, 4, 7, or 8) or degradation due to overgrazing (e.g. cases 3, 5, or 6). Such diagnoses were based not only on the absolute values of ESSI but also on the evaluation of ESSI trends over time (e.g. cases 1, 2, or 8). The usage of absolute values may help to describe ES supply heterogeneity at local scales. For example, cases 3, 5, and 6 showed how ESSI help to identify, within a management unit, different levels or states of conservation associated to both domestic herbivory or conservation policies. Interestingly, the index was useful to capture the influence of grazing on both forests and grasslands systems.

Nevertheless, the use of absolute values of ESSI at regional or subcontinental level may provide a confusing message to decision-makers (e.g. case 1). Differences in absolute values could promote to the prioritization of conservation in areas where ES supply is higher while relegating it in those areas with lower ES supply However, many ES (biodiversity, polinization, water supply, or flood regulating) should not be treated as interchangeable commodities because they are provided locally (Paruelo et al., 2015). On the other hand, ESSI trend analysis provides an integrative perspective on the sustainability of a given area (both at local or regional levels). Moreover, incorporating reference areas (e.g. National Parks or Protected Areas as representative of areas with the least human intervention) in the analysis, makes it possible to identify if trends were associated to global, regional or local factors or to human activities (e.g. protected areas in Argentina and Uruguay, cases 1 and 5 respectively). At regional or subcontinental level, combining ESSI mean and trends for the period 2000–2014 helped us to characterize the environmental status of a whole country (Argentina, case 1) or an entire ecoregion (Atlantic Forests in Brazil, case 2). In case 2 ESSI mean and trends combined with land use characterization allowed to identify and to quantify degraded, fragmented, healthy areas and also areas of progressive degradation and under restoration.

For half of the cases listed in Table 2 (cases 3, 4, 5, and 6) research and development (R&D) institutions generated a product that may help decision-making (Fig. 2). In cases 3, 5, and 6, previous links with stakeholders (ranchers) induced a demand on users. An important application of ESSI was its usage in adaptive management processes. A recent study (case 4) presented solid evidence on the impact of landscape configuration, particularly the distribution of forests strips on the supply of ES from the forests in the Semi-Arid

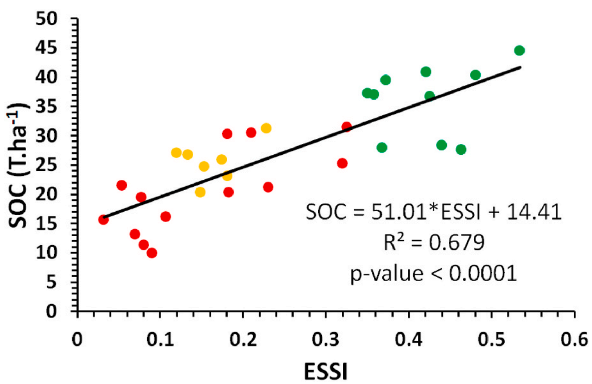

Fig. 1. Linear regression between soil organic carbon (SOC) content in the upper 20 cm (T.ha^{-1}) from 30 soil samples and ESSI mean to period 2000–2015.The green, orange and red points correspond to native forests, pastures and croplands, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Synthesis of 8 Ecosystem Services Supply Index (ESSI) cases of application. Each case is described according to which stakeholders originated the demand the study area in which it was applied, how it was used and its applications (actual and/or potential) in diagnosis, planning and/or monitoring of socio-ecosystems.

Cases of ESSI application and key references	Stakeholders who originated the demand	Study area	Description of ESSI use	Applications	
1. Assessment of the environmental situation of Argentina 2015 [1] Paruelo et al., (2015) [2] Milkovic et al., (2016)	NGO[a] Argentine Wildlife Foundation (FVSA[b]) - World Wildlife Fund (WWF)	Argentina	To characterize the environmental situation in terms of supporting and regulating ES supply, mean ESSI and its trend for the period 2000–2015 were characterized for the whole country with a spatial resolution of 1km. Additionally, ESSI trends within the national protected areas were compared with those of their contiguous areas to isolate the effects of local management from global or regional trends [1].	Diagnosis	A 20.8% of the country presented a significant reduction of the ESSI. Negative trends were mainly associated to either expansion or intensification of agricultural activities and arid and semiarid areas of Patagonia. Only a 0.8% of the country showed positive trends, mainly in irrigated areas. As in the whole territory, most of the protected areas presented negative trends. However, contiguous areas presented, on average, a reduction 19% greater than protected areas. This shows that the decrease in trends can be explained both by global or regional factors (e.g. climate change) and by local factors (e.g. land use change).
				Planning	An outreach article [2] for decision makers presented, among a series of recommendations, the possible use of ESSI both in reports for international conventions on biodiversity, climate change and desertification, as well as in land use planning processes and in environmental management programs.
				Monitoring	The same article presented an outline of a consortium of institutions from R&D sector and NGOs supported by government agencies to set up a protocol to regularly monitor ES supply.
2. Assessment of the status of Atlantic Forest in South America 2017 Fundación Vida Silvestre Argentina and WWF 2017	NGO[a] ArgentineaWildlife Foundation (FVSA[b], WWF-Brazil & WWF-Paraguay	Atlantic Forest from Brazil, Paraguay and Argentina	ESSI was used as an indicator of supporting and regulating ES supply in a report that compiles 15 years of contributions, lessons learned, and initiatives that represent important milestones in the implementation of nature conservation within the Atlantic Forest ecoregion in the three countries.	Diagnosis	Four categories of the Atlantic Forest state were identified from combining ESSI (mean and trends for the period 2000–2014) with land uses: 1) Degraded and fragmented areas, agricultural areas with mean or low ESSI values and decreasing or unchanged trends (74% of the area); 2) Healthy areas, remnants of native forest with high ESSI values and stable over time (10% of the area); 3) Areas of progressive degradation, deforested areas concentrated in Paraguay, with decreasing ESSI trends (9% of the area) and 4) Reconnection and reforestation areas, with increasing ESSI trends, where the recovery of native forests or commercial forest plantations is developed (7% of the area).
				Planning	The ESSI may contribute to the Atlantic Forest Ecoregional Program by identifying recovered forests on degraded lands and helping in the design of sustainable and resilient landscapes that integrate forest fragments, areas in recovery of natural cover and productive land.

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Table 2 (*continued*)

Cases of ESSI application and key references	Stakeholders who originated the demand	Study area	Description of ESSI use	Applications	
3. Forest degradation assessment along grazing gradients https://www.sciencedirect.com/science/article/pii/S0140196317301994Verón et al., 2018	R&D[c] INTA[d]	Province of La Rioja, Argentina (Dry Chaco forests)	ESSI was used to evaluate differences in the supply of supporting and regulating ES in woodlands devoted to livestock production and under different levels of degradation.	Diagnosis	ESSI showed a positive relationship with the conservation status of the woodlands. ESSI in non-degraded sites (located more than 7000 m from the watering point) was on average 19.6% higher than in degraded sites (located less than 200 m from the watering point).
				Monitoring	Because ESSI varied across the degradation gradient defined by grazing intensity it could be used as an indicator to monitor the status of woodlands devoted to livestock production.
				Planning	Monitoring degradation due to cattle grazing through the ESSI would allow designing livestock management strategies at the farm level.
4. Forest strips contribution to forest ES supply at the landscape level Camba Sans et al. (2019)	R&D[c] UBA[e] CONICET[f]	Provinces of Salta and Santiago del Estero, Argentina (Dry Chaco forests)	It was used to assess whether the structural connectivity of forests provided by forest strips contributes to increasing the supporting and regulating ES supply in forest patches.	Diagnosis	Landscapes with greater structural connectivity provided by forest strips showed high ESSI values in forest patches.
				Planning	Argentina has a national native forests law (N° 26.331) that requires provinces to carry out, every 5 years, a territorial planning of their forests. This implies inventorying and establishing conservation categories with restrictions on deforestation. Some categories allow partial deforestation, as well as conserve forests in form of forest strips exclusively. ESSI assessment could contribute to improve the current legislation by a better planning of the forest strips network at the landscape level that maximize support and regulation ES.
5. Assessment of the effect of protected areas on the ES supply Gallego et al. (2020)	R&D[c] UDELAR[h] INIA[i]	Grasslands from the Sierras del Este region, Uruguay (Río de la Plata Grasslands)	This case evaluate the supporting and regulating ES supply through ESSI of different vegetation under contrasting management practices by comparing a protected area with the surrounding landscape which has been subjected to human disturbance.	Diagnosis	The ESSI in grasslands and shrublands was higher outside the protected area than inside of it. On the other hand, woodlands showed higher ESSI inside the protected area than outside of it.
				Planning	Results are key in the development of management strategies tacking in account the different ecosystems within protected areas to preserve the ES provision. Grazing exclusion in protected areas does not necessarily lead to grassland and shrubland conservation. On the other hand, restricting disturbances appears to be the most appropriate management strategy to conserve woodlands.
				Monitoring	The ESSI could be used to monitor management strategies adopted within protected areas.
6. A functional assessment of vegetation heterogeneity derived from livestock management Altesor et al. (2019)	R&D[c] UDELAR[h] INIA[i]	Grasslands communcities of Uruguay (Río de la Plata Grasslands)	Altesor et al. (2019) characterized the degradation level of different grasslands communities in Uruguay through a states and transitions model analysis which was defined from field surveyed structural	Diagnosis	Despite the physiognomic homogeneity between states and phases, ESSI showed differences among different level of grassland condition.
				Planning	Given ESSI sensitivity to degradation status it can be used to identify different states or phases

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Table 2 (*continued*)

Cases of ESSI application and key references	Stakeholders who originated the demand	Study area	Description of ESSI use	Applications	
			attributes. Then, they assessed the ESSI differences among the different degradation states and phases.		within ranches and to design restoration actions through management actions.
7. Environmental liabilities assessment caused by illegal deforestation LART (2016)	Government agent National Ombudsman's Office of Argentina	Province of Salta, Argentina (Dry Chaco forests)	Based on complaints of illegal deforestation, the Ombudsman's office asked the Regional Analysis and Remote Sensing Laboratory of the University of Buenos Aires (LART[g], for its acronym in Spanish) toestimate the magnitude of ES loss in 22 farms (112,471 ha) illegally deforested in the Province of Salta (Expedient TRI-UBA: 0083942/2016, Note DPN N°3039/III).	Diagnosis	The year and area deforested on each farm was identified and the ESSI dynamics were estimated for the period 2006–2015, including years before and after deforestation. Two types of analysis were carried out to compare the magnitude of ES losses. One spatial (the level of ESSI in deforested areas with respect to neighboring forest areas), in which an average decrease of 40% was observed in deforested areas; and a temporal comparison (the level of ESSI in deforested areas before and after clearing), in which the average losses were even greater.
				Monitoring	Both deforestation monitoring (http://monitoreodesmonte.com.ar) and ESSI assessment provided key information in trials for illegal deforestation
8. Grasslands conservation assessment Staiano and Paruelo (2017)	Government agent The Board of Livestock on Natural Grasslands (MGCN[j]) through an agreement between Inter-American Institute for Cooperation on Agriculture (IICA[k]) and LART	Grasslands from the Centro-Sur region, Uruguay (Río de la Plata Grasslands)	The MGCN needed to advice MGAP[l] on the grassland conservation value over a large area of Uruguay (Centro-Sur region, 2.25 M ha), chosen because considered to be the most threatened by tree plantations and agricultural expansion. ES supply was one of the dimensions to consider. ESSI was mapped and considered in assessing grasslands value through a participatory process with multiple stakeholders, using multicriteria methods.	Diagnosis	ESSI was one of the 10 criteria applied to characterize the region at landscape level (25 km^2 cells). Maps of the proportion of grasslands within the 25 km^2 cells without negative trends in ESSI for the period 2000–2015 was produced. Based on the 10 criteria and in participatory definition of their weight, a grassland conservation value index was generated.
				Planning	Results are key in planning processes, i.e. in the definition of conservation and restoration areas. The geographic database generated provides key elements in the discussion of conservation tools (incentives, regulations) for native grasslands (Pereira Machín and y Morales, 2012)

[a] NGO - Non-governmental organization.
[b] FVSA - Fundación Vida Silvestre Argentina.
[c] R&D – Research and Development institutions.
[d] INTA – Instituto Nacional de Tecnología Agropecuaria (Argentina).
[e] UBA – Universidad de Buenos Aires (Argentina).
[f] CONICET – Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina).
[g] LART - Laboratorio de Análisis Regional y Teledetección (Argentina).
[h] UDELAR – Universidad de la República (Uruguay).
[i] INIA – Instituto Nacional de Investigación Agropecuaria (Uruguay).
[j] MGCN - Mesa de Ganadería sobre Campo Natural (Uruguay).
[k] IICA – Instituto Interamericano de Cooperación para la Agricultura.
[l] MGAP – Ministerio de Ganadería Agricultura y Pesca (Uruguay).

Chaco. The impact of the results of this study on decision-making could be articulated through two key actors and at two different scales. First, local enforcement authorities of the Native Forests Act may incorporate these results in future updates (scheduled every 5 years) of the Law. Second, farmers, have now key elements to plan the area, size, and location of the forest strips (INTA, 2019). Those cases generated from NGO's demands (cases 1 and 2) produced material devoted to decision-makers. However, the direct impact on defining policies was rather low. Probably the scale of these studies (subcontinental and regional) would restrict its application because it would need inter-institutional negotiations and the involvement of multiple stakeholders.

The cases presented have, so far, different levels of influence in decision-making process. For cases 7 and 8, those with the greatest influence, the demand originated from government agencies. In case 7 the differences in ESSI mean provide legal evidence of the environmental damages associated to illegal deforestation in Northern Argentina. The evidence provided by the index helped to prosecute lawbreakers of the Act 26.331 of Native Forest protection in Argentina. Losses in ES supply characterized through the ESSI along with evidence demonstrating the recovery of ecosystem functioning in deforested, cultivated and then abandoned areas (Basualdo et al., 2019), gave rise to an unprecedented judicial ruling, from which the justice ordered to stop farming and to restore illegally deforested areas (Act 4013/11, Repetto, 2019). Case 8 showed the role of spatially explicit, empirically validated and socially accepted metrics in planning and decision-making. The Board of Livestock Production on Native Grasslands of Uruguay (an inter-institutional consortium oriented to discuss and coordinate public policies, constituted by government agencies, academia, ONGs and ranchers associations) asked for a characterization of the conservation value of the grasslands over a subregion of Uruguay (more than 2 million ha). ESSI trends were used, together with other indicators, for assessing the conservation status of grasslands at the landscape level and supporting decisions on which landscapes should have more conservation efforts. In both cases (7 and 8), the ESSI was used together with other indicators, complementing descriptions that cover other environmental dimensions (i.e. biodiversity, restoration potential, etc.).

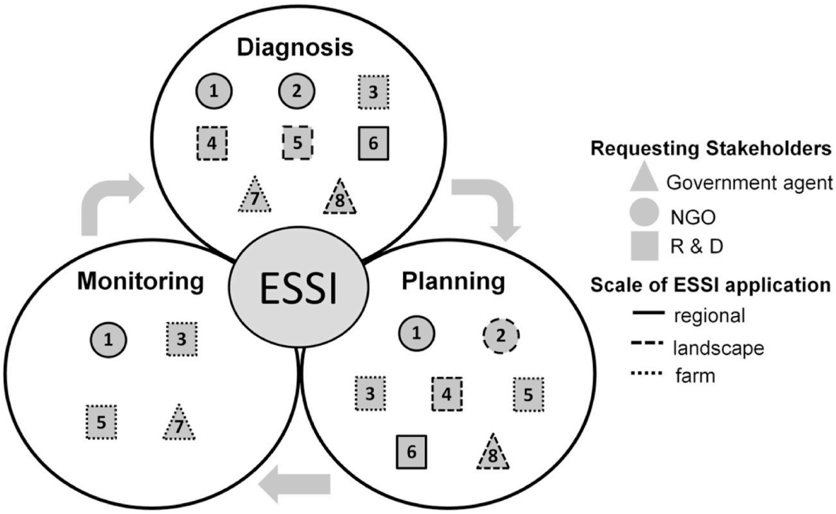

Fig. 2. Cases of Ecosystem Services Supply Index (ESSI) application in different territorial planning stages. The numbers correspond to 8 cases: Assessment of the environmental situation of Argentina (1), Assessment of the status of Atlantic Forest (2), Forest degradation assessment along grazing gradients in La Rioja, Argentina (3), Forest strips contribution to ES supply at the landscape level in Semi-Arid Chaco forests (4), Assessment of the effect of protected areas on the ES supply in Sierras del Este region, Uruguay (5), A functional assessment of vegetation heterogeneity derived from livestock management in Uruguayan grasslands (6), Environmental liabilities assessment caused by illegal deforestation for its use in legal trials in Salta, Argentina (7), Grasslands conservation assessment in Centro-Sur region, Uruguay (8). Descriptions of the applications are developed in Table 2. The symbols indicate the stakeholders who originated the demand (Government agencies, Research and Development institutions (R&D) and Non-governmental organizations (NGOs) and their borders indicate the scale of each application (regional, landscape or farm).

4. Implications, scopes, and limitations of the ESSI use

So far, the ESSI proved to be a good indicator of the level of supply of some supporting and regulating ES linked to water and carbon dynamics and biodiversity in the Dry Chaco (SOC, groundwater recharge and avian richness) and the Río de la Plata Grasslands (SOC, evapotranspiration and avian richness) ecoregions (Table 1). The empirical evaluations of the index support its use as a proxy for the level of ES supply in the application cases presented (Table 2). Three main advantages associated with its use can be identified. The first one is that since it is an index derived from spectral data provided by remote sensors, it is possible to make estimations over large areas and during long periods (i.e. decades), with a high temporal resolution, at a low cost, and with the same protocol, without the need to interpolate or extrapolate specific observations (Paruelo et al. 2014). The second one is that it provides the possibility to analyze trends early since it is based on two attributes of ecosystem functioning, which tend to respond faster to changes in environmental conditions than structural attributes (e.g. changes in the physiognomy of the vegetation) (Milchunas and Lauenroth, 1995; Paruelo et al., 2004;

Paruelo, 2008).

Lastly, the functional attributes that constitute the ESSI are based on the NDVI, a vegetation index widely used in remote sensing, which is easy to estimate and can be obtained from data provided by a wide range of sensors on board of Earth observation satellites with a variable spatial and temporal resolution (Pettorelli, 2013; Paruelo et al., 2014). In both, the evaluation and application cases presented, the NDVI was obtained from satellite images from the MODIS sensor (MOD13, Vegetation Indices 16-Day L3 Global), whose temporal resolution is 16 days and the more detailed spatial resolution it offered is 250m. In the ESSI application cases, this allowed its use at the regional (cases 1, 2, and 6), landscape (cases 4 and 8), and farm level (cases 3, 5, and 7) (Fig. 2). While a possible limitation is that until now, the ESSI has not been estimated at more detailed spatial scales (sites or areas smaller than 250m x 250m). The increasing development of new sensors that provide images with high temporal and spatial resolution would allow the ESSI to be obtained at more detailed spatial scales (e.g. images from the Sentinel-2 constellation with a spatial resolution of 10m and temporal resolution of 5 days).

The use of the ESSI in the context of the cascade model (Boyd and Banzhaf, 2007; Fisher and Turner, 2008 ; de Groot et al., 2010; Haines-Young and Potschin, 2010; Paruelo et al., 2016), represent a quick and easy way to estimate the human impact on intermediate ES. An advantage of this aspect is that quantifying indicators of some intermediate ES is easier than quantifying any of the final ES it determines, which in turn is easier to quantify than the benefits. This means that going down the cascade involves making the estimation more complex. At the same time, estimating intermediate ES (at the beginning of the cascade) allows to homologating the level of ES supply in landscapes that provide different final ES (Fisher et al., 2009). Thus, the index is not necessarily quantifying the final ES supply. Moreover, it tells nothing about the real benefits for different stakeholders. Quantifying benefits involves linking the final ES to social interests, values, and needs. These aspects vary depending on who appropriates these benefits and how they are defined. Therefore, the generation of benefits depends on the actual ES demand and how these are converted into benefits perceived by society (Yahdjian et al., 2015). There is evidence that hotspots of ES supply and demand do not necessarily match (Laterra et al., 2016; Nahuelhual et al., 2016), therefore a proper description of ES demand is critical in defining environmental actions or policies.

Like any indicator, the ESSI has limitations that need to be considered in order to avoid misinterpretations. Some of the shortcomings may derive from the degree of correlation among the ES that constitutes a bundle. We illustrate this with two examples. First, there is no generalizable equivalence between the ESSI and each ES. For example, while it is possible to estimate the SOC content given a specific value of the ESSI in Chaco (Fig. 1), surely its possible that the parameters (intercept and slope) of this relationship are not able to estimate the SOC in Río de la Plata Grasslands (Paruelo et al., 2016). Due to the higher precipitation/temperature ratio (Alvarez and Lavado, 1998), higher SOC content is usually observed in the last region. Furthermore, the relationships between ESSI and SOC were different in both regions, in the Río de la Plata Grasslands a non-linear model was applied (Paruelo et al., 2016, Table 1), while in Chaco the relationship was evaluated with a simple linear regression (Fig. 1). In turn, LULCC affect differently the SOC content in both regions. Projections based on temporal models showed that after 60 years of agricultural use in the Río de la Plata Grasslands (Caride et al., 2012) the SOC would be 15% lower than the reference value (grassland), while in Chaco (Villarino et al., 2017) the decrease would be around 45% respect to the forest (Paruelo and Dieguez, 2019). In this sense, the ESSI is used as a proxy for different ES, and increasing its accuracy in the estimation of specific ES requires local calibrations that depend on incorporating other factors that make the estimation more complex.

A second example is that the replacement of natural vegetation by tree plantations in the Río de la Plata grasslands, which may increase the ESSI (due to an increase in $NDVI_{MEAN}$ and a decrease in $NDVI_{CV}$, Vassallo et al., 2013), will not necessarily imply an increase in SOC (Eclesia et al., 2012). This LULCC also increase evapotranspiration (Nosetto et al., 2005) and decrease the hydrological yield, which will not necessarily imply an increase in the water supply (Jobbágy et al., 2006, Jobbágy et al., 2013). In this case, the correlation among water supply, biodiversity, and C gains would be low or even negative. ESSI provide a synoptic view, but its interpretation depends on the context and it must be evaluated together with additional, complementary information. In this sense, it is also important to enhance the assessment of the ESSI with other ES in different ecosystems, landscapes and regions and considering different stress or perturbation factors. As in Human health evaluation diagnosis and therapies can not be based on a unique indicator and, a lot less, without a “clinical” evaluation.

Having synoptic indicators that feedback on the diagnostic-planning-monitoring cycle (Fig. 2) is key in territorial planning, since it allows for a rapid and continuous evaluation of the consequences of management actions. Finding land use strategies to meet sustainable development goals has been incorporated into the research and decision-making agenda (e.g. UN Sustainable Development Goals, IPBES). Land use alternatives, and particularly those that involve some sort of intensification, must be evaluated in terms of its economic, social and environmental sustainability. However, to quantify sustainability in absolute terms is virtually impossible. As far as ES supply can be characterized, it is possible to advance in an operational definition of the level of sustainability and to quantify it across agricultural intensification gradients or land uses alternatives. In this context, the ESSI may provide a useful tool to compare and decide between land uses strategies such as “land-sharing”, “land-sparing”, a combination of both (Perfecto and Vandermeer, 2010; Phalan et al., 2011; Fischer et al., 2014; Kremen, 2015), or to evaluate spatial and temporal land use diversification alternatives at the landscape level (Landis, 2017; Garibaldi et al., 2019).Moreover, the potentially complete spatial cover provides by remotely sensed indicators becomes particularly important in a context of global change, because it makes it possible to tell apart the effects of its different dimensions (changes in climate, land use, biodiversity, or biogeochemical cycles). A metric such as ESSI, that allows comparing trends in situations subject to a differential influence of these dimensions, would make it possible to generate quantitative hypotheses of the importance of each one of them (Garbulsky and Paruelo, 2004; Dieguez and Paruelo, 2017).

5. Concluding remarks

The empirical support compiled showed that ESSI is a synoptic indicator and a good proxy for the level of supply of some supporting and regulating ES related to carbon and water dynamics. The new empirical evidence presented reinforced the existing one, since the ESSI was able to explain 68% of the variability in soil organic carbon in Dry Chaco forests. The ESSI was successfully applied for diagnosis, monitoring, and planning processes by multiple stakeholders including NGOs, government agencies, scientists, judicial authorities, among others. The index generally showed sensitivity to LULCC and degradation processes and was easy to calculate with available (and free) remote sensing data. The analyzed cases showed that using an empirical validated index of ES supply helped to better define interventions both in management decisions and in issues that involve environmental conflicts. Having a spatial explicit description of ES supply helped to empower the most vulnerable stakeholders in territorial and environmental conflicts.

CRediT authorship contribution statement

Luciana Staiano: Conceptualization, Methodology, Investigation, Writing – original draft, Data curation, Visualization. **Gonzalo H. Camba Sans:** Conceptualization, Writing - review & editing, Visualization. **Pablo Baldassini:** Formal analysis, Writing - review & editing, Visualization. **Federico Gallego:** Writing - review & editing. **Marcos A. Texeira:** Writing - review & editing. **José M. Paruelo:** Conceptualization, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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