



Review Article

Ecosystem service research in the dry subtropics: Current state, temporal changes and drivers of regional variability

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Abstract

Dry subtropical (DST) regions that share similar climatic and topographic conditions exhibit today significant disparities in population density, agricultural intensity, wealth and cultural values. In addition, they are also facing increasing pressures on their natural resources. These attributes collectively shape individuals' varying dependence on natural resources and may influence their perception of ecosystem services (ES). In this study, we conducted a systematic literature review, focusing on the DST regions, to address two main questions: 1) What is the current state, temporal trends and regional variability in scientific research on ES and 2) What are the potential drivers of the variability in ES research? Amongst the 471 publications found in our review, 53% focused on provisioning services, followed nearly equally by cultural (33%) and regulating (30%) services. Only 13% addressed more than one ES category and approximately 33% mentioned economic valuation. Our study reveals that research on ES in the dry subtropics experienced a significant increase from 2005 onwards. Approximately 45% of the publications included the term 'ecosystem service' and its frequency has risen substantially over time. Most publications primarily focus on African dry subtropics (over 60%), followed by South and North American ones. Publications from southern Asia and NE Australia were more scarce. Importantly, we found no clear relationship between the number of publications, publication

density or representativeness and the variables used as indicators of human pressure (e.g. population density). Consequently, research efforts in the DST regions appear to be influenced by a diverse range of financial and institutional constraints, international research agendas, as well as the personal interests of researchers, contributing to the idiosyncratic nature of this field.

Keywords

Drylands, cultural drivers, temporal trend, thematic gaps, geographic gaps

Introduction

Ecosystem services (ES) rely on biophysical structures and processes delivered by living organisms, ultimately leading to benefits for human well-being (Costanza et al. 1997, MEA 2005, Haines-Young and Potschin 2010). The structure and functioning of ecosystems are broadly influenced by biophysical variables, such as climate, topography, soil and biota characteristics (Holdridge 1947, Webb et al. 1983, Woodward et al. 2004, Del Grosso et al. 2008). It is reasonable to assume that regions with similar physical environments and vegetation type may potentially provide comparable ecosystem services. However, even under similar biophysical conditions, the perception of benefits can significantly vary depending on society's needs, land-use choices and moral values (e.g. religion, emotions) (Haines-Young and Potschin 2010, García-Llorente et al. 2020). This distinct perception may, in turn, shape the research questions addressed by the scientific community and guide regional or country-wide environmental agendas. An ecological structure like a woodland, for instance, may have the capacity (or function) to reduce surface runoff, providing what is considered a regulating service that produces the benefit of decreasing the probability of flooding. However, whether this function is considered a service depends on the value that society gives to this benefit. Even though this example may be an oversimplification (Costanza et al. 2017), these ideas are framed in the ecosystem service cascade conceptual framework that relates function, ecosystem services and benefits to humans (Haines-Young and Potschin 2010, Mastrangelo et al. 2015).

Dry subtropical (DST) regions, widespread across the globe, share similar climatic and topographic conditions and were originally dominated by woodlands and savannahs (Schimper et al. 1903, Olson et al. 2001). Notably, these regions currently display some of the most pronounced cultural disparities within a given biome. This variability in human impact arises from significant differences in population density, extent and intensity of agriculture, fate of production (from subsistence to industrial commodity production), wealth and cultural or ideological values (Baldi and Jobbágy 2012, Parr et al. 2014, Schröder et al. 2021, Camino et al. 2023). Importantly, their natural resources face mounting pressures as a result of population growth, rising affluence and their integration into global markets (Parr et al. 2014, Gasparri et al. 2016, Buchadas et al. 2022). All these attributes collectively shape the varying dependencies of individuals on natural resources across regions, alongside their capacity to harness these resources (Pratzer et al. 2024).

As a result, these factors inherently influence their perception of ecosystem services. Hence, DST located in Africa, Asia, Australia, North America and South America offer nowadays a valuable setting to explore alternative ecosystem services importance, differential perceptions, independently of the environmental constraints.

Under the framework given by the DST regions, we propose two guiding questions:

1. What is the current state, temporal trend and regional variability in ES scientific research?
2. What are the potential drivers of the variability in ES research across regions?

Under the first question, we aim to achieve a general description of ES studies taking into account the ES (sub)category, mention of monetary valuation, identification of applicants/beneficiaries, analytical approach, spatial extent and publication language. In addition, we specifically explore how frequent the term “ecosystem service” is mentioned in the publications. In the second question, we evaluate the drivers of geographical variability in ES research exploring, in particular, demographic pressure, affluence, geographical isolation and land use/cover. Given that ecosystem service research is an applied science field aiming to elevate the consideration of nature services in decision-making (Mandle et al. 2020), we consider that – ideally - research should be closely related to the characteristics and evolving needs of local populations within changing cultural and biophysical territories. The level of total demographic pressure would indicate the baseline of local demands on natural resources (DeFriest et al. 2010, Crist et al. 2017). The level of affluence would be related to the degree of reliance of local population on natural resources and to its capacity to appropriate them (lower reliance, but higher capacity in wealthier areas and vice versa) (Reardon and Vosti 1995, Gray and Moseley 2005). Finally, the level of geographical isolation of a territory would also be indicative of the local population reliance on natural resources, their ability to access external supplies (e.g. including food, materials, technology) and the feasibility of exogenous actors to enter and appropriate natural resources (e.g. tourists, agribusiness companies) (Stifel and Minten 2008, Dorosh et al. 2010). For the first question, the main variable of interest is the number of publications. For the second question, we use density (publication number by regional extent) and representativeness (ES category publication number/ES total publication number) as response variables, both of which are derived from the number of publications.

We have the following predictions:

1. In contexts of high population density, low affluence and high isolation from markets, provisioning ES publications are likely to predominate.
2. In contexts of high land-cover transformation and easy access to markets, regulating ES publications are likely to predominate.
3. Additionally, we anticipate that, in areas with greater amounts of uncultivated land and protected areas, we will find more cultural ES publications.

Evaluating the current state of ecosystem service research across regions can help identify environmental agendas from both the scientific, as well as government sectors.

Simultaneously, this assessment can provide insights into society's perception of the benefits associated with ES delivery. In addition, analysing the growing body of literature on ES may be useful to pinpoint knowledge gaps (both geographic and thematic), shape policy tools to mitigate environmental problems and, in particular, try to explain the potential differences in ES research efforts amongst regions.

Material and methods

Distribution of dry subtropical regions

We focused our study on five dry subtropical (DST) regions located in Africa (namely Zambezi-Kalahari), Asia (India-Pakistan), Australia (Northeast -NE- Australia), North America (Mesquite) and South America (Chaco) following the biophysical delimitation provided by Baldi and Jobbágy (2012) (Fig. 1). These regions account for $6.4 \times 10^6 \text{ km}^2$ (5% of the global land area, excluding Antarctica) and encompass predominantly woody vegetation and were delineated, based on similar climatic and topographic features: dry winters/wet summers (> 66% of precipitation in the warm half of the year, i.e. October-March in the Southern Hemisphere and April-September in the Northern Hemisphere), mild temperature conditions (mean annual temperature from 20°C to 25°C), semi-arid to sub-humid conditions, as defined by the ratio of mean annual precipitation to potential evapotranspiration (PPT:PET, from 0.2 to 1.0, implying a PPT from 300 to 1500 mm), an altitude < 1200 m a.s.l. and a flat topography (terrain slope < 0.7°) (Table 1).

Table 1.

Characteristics of the five dry subtropical regions according to Baldi and Jobbágy (2012). * data missing for western Paraguay.

Region	Countries	Area ($1 \times 10^3 \text{ km}^2$)	Cultivated (%)	Protected (%)	Population density ($\text{inh} \cdot \text{km}^{-2}$)	Infant mortality rates (‰)	Isolation (min)
Chaco	Argentina/ Bolivia/ Paraguay	1061	15.9	5.5	7.3	28*	494
India-Pakistan	India/Pakistan	834	73.9	2.1	465.5	101	130
Mesquite	Mexico/ United States of America	237	12.5	0.3	25.3	17	181
NE Australia	Australia	823	2.4	0.9	1.0	6	483
Zambezi-Kalahari	Angola/ Botswana/ Eswatini/ Malawi/ Madagascar/ Mozambique/ Namibia/ South Africa/ Tanzania/ Zambia/ Zimbabwe	3483	11.4	13.7	21.6	102	599

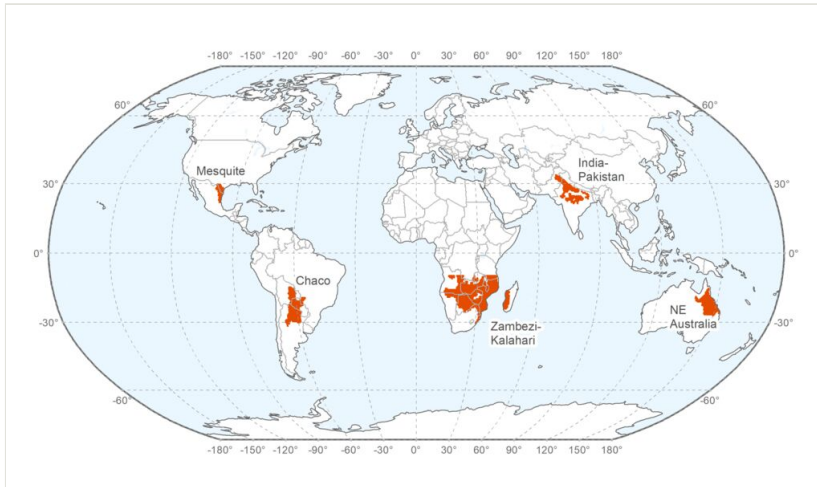


Figure 1.

Distribution of the five dry subtropical regions (in red) according to Baldi and Jobbágy (2012).

Focus ecosystem services and bibliographic databases

In our review, we considered publications that assessed provisioning, regulating and cultural ecosystem services. We also considered only those services provided by woody-dominated systems, such as forests, woodlands, shrublands, savannahs, wetlands with woody components or woody steppes. Studies of services provided by cultivated, coastal or urban ecosystems were, therefore, discarded. The list of ES categories and subcategories is depicted in Table 2, while the ES keywords are in Suppl. material 1. Our classification followed the Millennium Ecosystem Assessment scheme (MEA 2005). However, we referred to the MEA category "Fibre" as "Material and fuel" and we added "Educational" into "Cultural services".

Table 2.

List of ecosystem services (ES) considered in this study (categories, subcategories and examples).

ES category	ES subcategory	Examples
1- Provisioning	a) Material and fuel	Household energy consumption: fuelwood, dung cake in Haryana, India (Qureshi and Kumar 1996); koala and possum capture for fur in Queensland, Australia (Hrdina and Gordon 2004).
	b) Food	Wild plants gathering in Mato Grosso do Sul, Brazilian Chaco (Bortolotto et al. 2019); hunting and consumption of mammals and birds in Madagascar (Randrianandrianina et al. 2010).
	c) Medicine	<i>Mondia whitei</i> as medicinal plant in African countries (Aremu et al. 2011); medicinal plant to treat chicken diseases in Zambia (Syakalima et al. 2017).
2- Regulating	a) Pollination	Wild pollinators of soybean flowers in Argentinean Chaco (Monasterolo et al. 2015).

ES category	ES subcategory	Examples
	b) Pest control	Natural enemies of maize stemborers in Zimbabwe (Chinwada and Overholt 2001).
	c) Water and climate regulation	Control of water fluxes by forest (Magliano et al. 2016) and potential of native forests for the mitigation of greenhouse gases (Manrique et al. 2011) in Argentinean Chaco.
3- Cultural	a) Recreation and tourism	Tourism initiatives on communal land in Namibia (Ashley 1998).
	b) Cultural and spiritual	Sacred groves and their significance in India (Khan et al. 2008).
	c) Education	Environmental education programmes in Texas, US (Griffin et al. 2016).

We did not consider publications dealing with:

- supporting services, such as productivity, soil formation or nutrient cycling;
- theoretical issues (e.g. analyses of the differences between terms such as "ecosystem services" and "Nature's Contribution to People" (Díaz et al. 2018b);
- payments for ES with no individual service acknowledged (e.g. Farley and Costanza (2010));
- biodiversity;
- synthetic calculations of ES through remotely-sensed data, when only linked to ecosystem properties.

Following Fisher et al. (2009), we excluded what are named "intermediate services", such as primary productivity, that have rather indirect benefits to humans.

We retrieved ES publications from two electronic databases, Scopus (<https://www.scopus.com/>) and SciELO (<https://scielo.org/>). Scopus database is proprietary and covers nearly 82.4 million scientific records worldwide. SciELO database is free-access and covers nearly 574,000 Ibero-american and South-african scientific records either in Spanish, Portuguese and English. The criteria used to retrieve publications dealing with the ES described in Table 2 are depicted in Suppl. material 1. These criteria also included a geographic list of keywords in order to retrieve publications within the dry subtropical regions. In these keywords, we included political (e.g. "Bolivia", "Lualaba"), as well as biogeographical (e.g. "Brigalow Tropical Savannah") items, also depicted in Suppl. material 1. The bibliographic search was conducted on 10 December 2023 and on 5 May 2024 and papers up to the year 2020 were included.

Once we defined the final bibliographic database, we characterised each publication by eight attributes: ES category (provisioning, regulating or cultural), ES subcategory (as indicated in Table 2), publication language, inclusion of monetary valuation (yes/no), identification of applicant/beneficiary (internal or external to the region), analytical approach (quantitative or qualitative), spatial extent (local, regional or global) and the mention of "ecosystem service" term (yes/no).

Then, we aimed to evaluate the relationship between the number of publications, publication density and representativeness (dependent variables) and their potential drivers of geographical variability (independent variables). Publication density is defined as the number of articles by the extent of the region (publications $1 \times 10^{-5} \text{ km}^{-2}$), while representativeness is defined as the ratio given by the number of publications of one ES category (or subcategory) and the total number of publications (or the number of publications in that category). The driving variables considered were: land-cover/land-use, demographic pressure, geographical isolation and the affluence of the local population. Land-cover was characterised from the synthesis of local land-use/land-cover products (Agrawal et al. 2003, Eva et al. 2004, Homer et al. 2004, Latifovic et al. 2004, Mayaux et al. 2004, BRS 2006). Demographic pressure was characterised from the SEDAC-CIESIN-CIAT “2020 Population of the World, Population density” v.4.11. The isolation of the territory, from the “Travel Time to Major Cities 2015” product, which describes the travel time to large cities (between 500,000 and 50,000 - class 6) by using a least-cost path algorithm (Nelson et al. 2019) and the affluence of the local population, from the “Infant mortality” v.2.01 from subnational statistics (CIESIN, Columbia University - 2021).

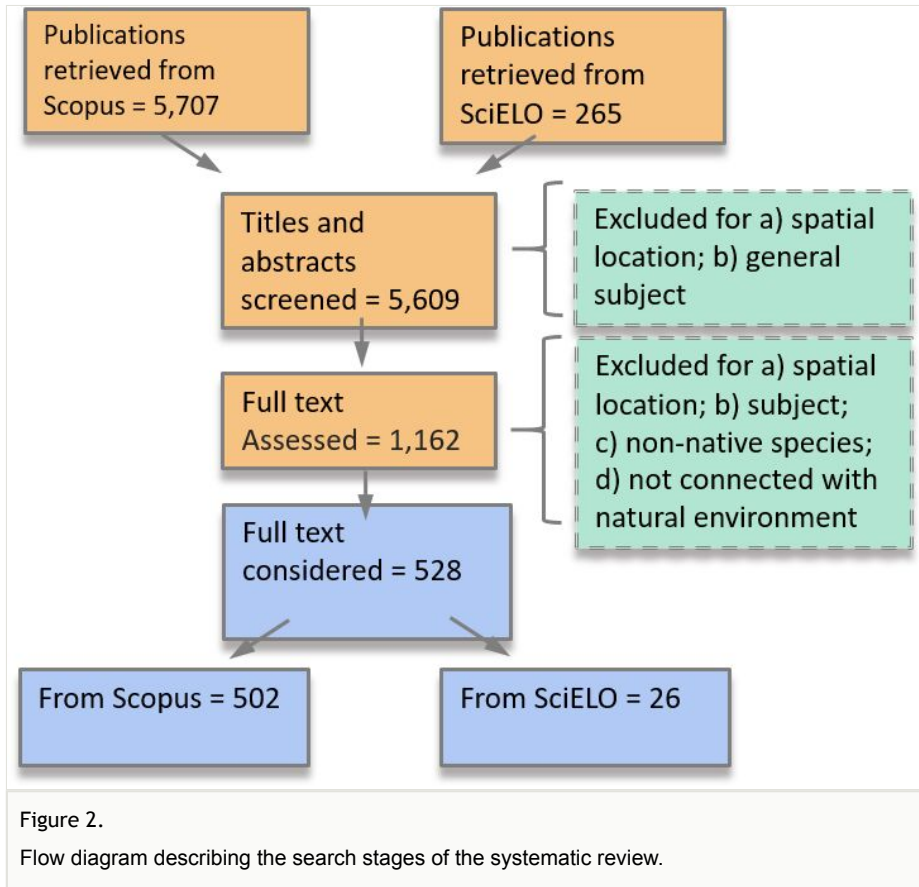
Results

Scientific, peer-reviewed, knowledge

Initially, a total of 5,609 publications were retrieved from our first search, but soon after the screening for titles and abstracts, 80% of them were excluded, primarily because they did not actually address the subject of ecosystem services or were outside our studied regions. Secondly, of the 1,162 full-publications addressed, 634 were excluded because they did not fulfil the more specific subject criteria: they included a non-native species as a target species (e.g. exotic parasitoids or predators), were not connected to a natural area (e.g. experimental studies conducted in greenhouses), considered “supporting services” or ecosystem functioning variables (such as primary productivity dynamics), focused on species diversity or composition or discussed payments for ecosystem services without an ES evaluation (e.g. publications with an ecological economy approach without a specific link to an ES) (Fig. 2). Of the remaining 528 publications (Suppl. material 2), 95% came from Scopus and 5% from SciELO databases. Our search included not only publications written in English (485), but also those in other languages, specifically, 29 written in Spanish (three of them also written in English), seven in Portuguese, four in German, two in French and one in Slovak.

Of the 528 publications, 48% studied provisioning services, followed by regulating (39%) and cultural (30%) services. Sixty-five publications (12%) included more than one category of service and, amongst these, cultural and provisioning services were the ones more commonly studied together (Fig. 3a). Only 17 publications mentioned the three ecosystem service categories. In the case of subcategories, amongst the publications dealing with provisioning services, nearly 25% mentioned all considered subcategories (i.e. materials and fuel, food and medicine) and this was much less common in regulating and cultural publications (i.e. the interception of the three subcategories accounted for 1 - 6% of the

publications) (Fig. 3b-d). Publications that mentioned two of the three subcategories were also relatively uncommon for both regulating and cultural services, especially in the case of pest control and water/climate regulation or cultural and spiritual and education that were not ever studied together. It is also important to highlight that, within the water/climate regulation subcategory, more than 65% of the publications addressed climate regulation focusing on C sequestration, while only three of them were about albedo changes.



Approximately 32% of the publications included economical valuation and the proportion was maximum for cultural services publications (approximately 52%), followed by provisioning publication (33%), while it was less common in studies that addressed regulating services studies (16%) (Table 3). Nearly 80% of the studies identified an applicant/beneficiary and, in most cases, it was internal to each region. This was especially true for provisioning service publications (75% of the publications identified an internal applicant). Publications that identified both internal and external applicants were more common in studies that addressed cultural services (24%). Most of the studies used a quantitative approach (80%) and were conducted at local or regional levels (70 and 28%, respectively). Only five studies addressed questions at a global level.

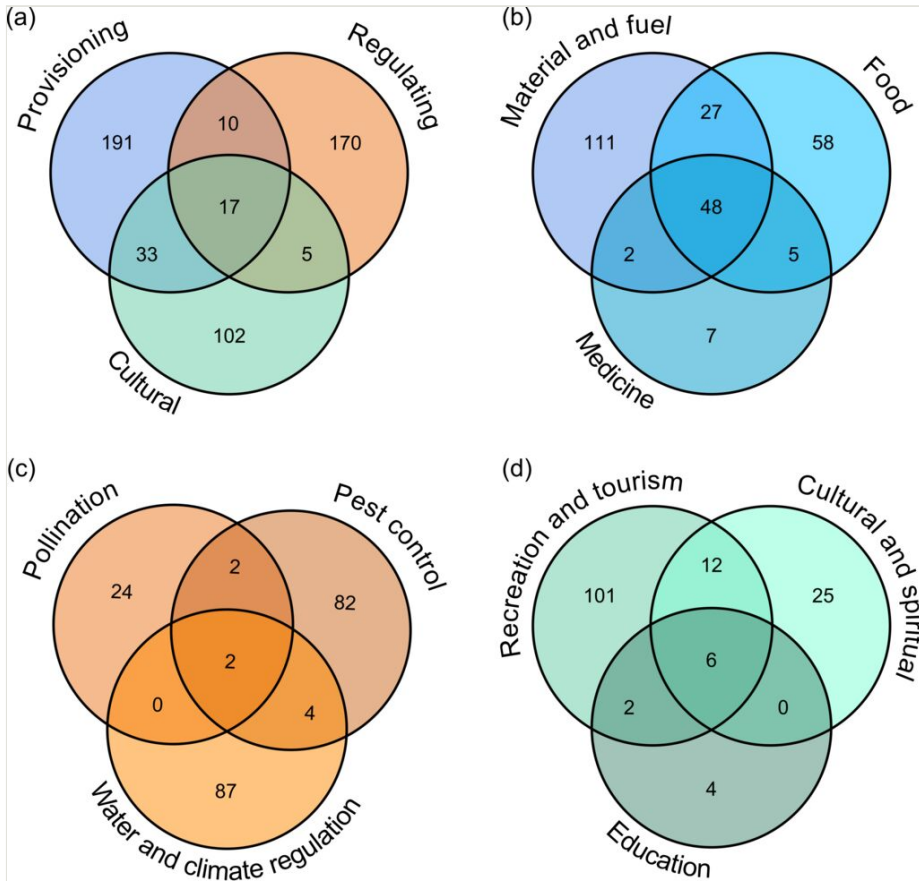


Figure 3.

Venn diagram indicating the number of publications in each (a) ecosystem service category and (b-d) subcategory.

Table 3.

Number of publications in the different ES categories that included an economical valuation, identified different types of applicants, used different approaches (qualitative or quantitative) or spatial extent (global, regional and local) and mentioned the term “ecosystem service”.*¹

ES category	Economical valuation*	Type of applicant				Approach		Extent			ES mentioning*
		Internal	External	Both	Not identified	Qual.	Quant.	Global	Regional	Local	
Provisioning	82/251	185	5	37	21	44	203	2	84	162	123/251
Regulating	33/202	60	6	28	95	26	163	2	59	128	99/194
Cultural	82/157	94	12	37	10	42	111	2	36	114	68/157

Since the earliest publication dating back to 1970 about wildlife utilisation in Botswana (Child 1970), the number of studies about our subject of interest has increased year by year in our study system, with a significant uptick from 2005 onwards (Fig. 4a). While this pattern of increasing publications is expected given the rise in global scientific publications (Bornmann and Mutz 2015), the significant increase post-2005 and the relative prominence of the term 'ecosystem services' in more recent publications are noteworthy. Approximately 45% of all publications included the term “ecosystem service” in their title, abstract or keywords. Surprisingly, this term was mentioned in an article published in 1971 (Smith 1971), although the “ecosystem service” concept burst in the literature in the 2000 decade (for an historical revision, see Costanza et al. (2017)). The frequency of the publications that mentioned “ecosystem service” increased substantially through time and they represented more than 55% of our search results for each year after 2015. The exponential growth rate for the publications that mention ES was almost three times higher than that of the publications not mentioning ES (increase rate for the exponential model = 0.17 ± 0.01 and 0.06 ± 0.007 , respectively) (Fig. 4b). The inclusion of the term “ecosystem service” was similar in the different ES categories (approximately 40%) (Table 3) and it was much more common in publications that studied more than one ES category (from 50 to 100%). The prevalence of studies focused on provisioning services has been sustained over time (Fig. S1a, Suppl. material 3).

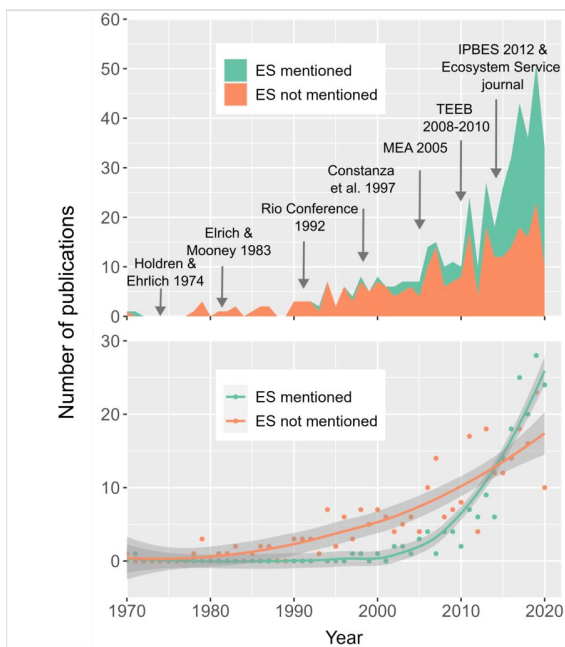


Figure 4.

Number of publications over time. In (a) stacked values of the number of publications mentioning or not the concept “Ecosystem Services” and (b) non-linear model fits for unstacked values. References in panel (a): Holdren and Ehrlich (1974), Costanza et al. (1997) Ehrlich and Mooney (1983), MEA (2005), TEEB (2010), IPBES (2019).

Amongst the regions, most of the publications focus in Zambezi-Kalahari (more than 60%), followed by Chaco and Mesquite (12% and 10%, respectively). Publications from India-Pakistan and NE Australia regions were more scarce (8% and 6%, respectively) (Fig. 5). Publications dealing with provisioning services were particularly important in Zambezi-Kalahari and Chaco (around 50%). This pattern in the Zambezi-Kalahari region accounted for the predominance in the overall count. In Mesquite and NE Australia, regulating services publications out-competed provisioning services articles. In the India-Pakistan region, provisioning and regulating services studies were equally common. Importantly, in Zambezi-Kalahari cultural services studies accounted for 32% of the found articles and, hence, this ES category was more common than regulating services articles. The few publications focusing NE Australia explored predominantly regulating and cultural services, while provisioning services received less attention (represented less than 20% of the publications in this region). When considering ES subcategories, in the case of provisioning, materials and fuel studies were predominant in all regions except Chaco, where the studies that mentioned food (wildlife hunting/harvesting, wild food/protein/meat/honey, non-crop food, Suppl. material 2) were more common (Fig. 6a). Medicine was included in relatively fewer studies. In the case of regulating services, pest regulation was clearly prevailing in all regions, followed by pollination studies, except in Chaco, where water regulation was mentioned in 48% of the studies (Fig. 6b). Tourism and recreation was the most numerous subcategory amongst the articles that studied cultural services in all regions (Fig. 6c), accounting for more than 40% of the studies in every region and even reached 70% of the cultural studies in Zambezi-Kalahari. The temporal trend of publications at the regional level mirrored the overall trend, with a continued predominance of Zambezi-Kalahari over time (Fig. S1b, Suppl. material 2).

Drivers of geographical variability

We found no clear relationship between the extent of the DST and the total number of ES publications (Fig. 7a). This implies that the effort on the study of ES provided by woody ecosystems across the globe is probably idiosyncratic, with Mesquite achieving the highest publication density values ($20.1 \text{ articles } 1 \times 10^{-5} \text{ km}^{-2}$), followed by Zambezi-Kalahari ($8.6 \text{ articles } 1 \times 10^{-5} \text{ km}^{-2}$) and with the remaining three regions with low and similar values (3.8 to $5.3 \text{ articles } 1 \times 10^{-5} \text{ km}^{-2}$). This idiosyncratic characteristic further appeared when analysing the number of publications along gradients representing human pressures. Neither the population density, the infant mortality, nor the isolation seem to drive the total number or the density of publications at a regional level (Fig. 7b-d and S2, Suppl. material 2). However, our findings indicate that the representativeness of studies on provisioning ES is higher in less affluent regions, such as India-Pakistan and Zambezi-Kalahari (Fig. 8b). Apart from that, our predictions about the representativeness of provisioning, regulating and cultural categories along the gradients of human pressure were not sustained (Fig. 8a, c-g).

When examining specific subcategories, we found that publications related to materials and fuels (e.g. charcoal) were more prevalent within the provisioning category for less affluent local populations, exceeding publications related to food or medicine (Fig. S3a-b,

Suppl. material 2). The level of agriculturalisation, contrary to what we expected, showed no relationship with the representativeness of pollination and pest control publications. As an example, Mesquite had the highest representation of these ES subcategories, despite having only 12.5% of the territory being dedicated to agricultural production (Fig. S3c, Suppl. material 2). We found some support for our prediction about cultural ES, as recreation and tourism publications were highest in Zambezi-Kalahari (n = 103) and similar in the other four regions (between four and nine studies). The majority of publications in Zambezi-Kalahari dealt with these non-consumptive activities within the 477,200 km² of protected areas (Fig. S3d, Suppl. material 2).

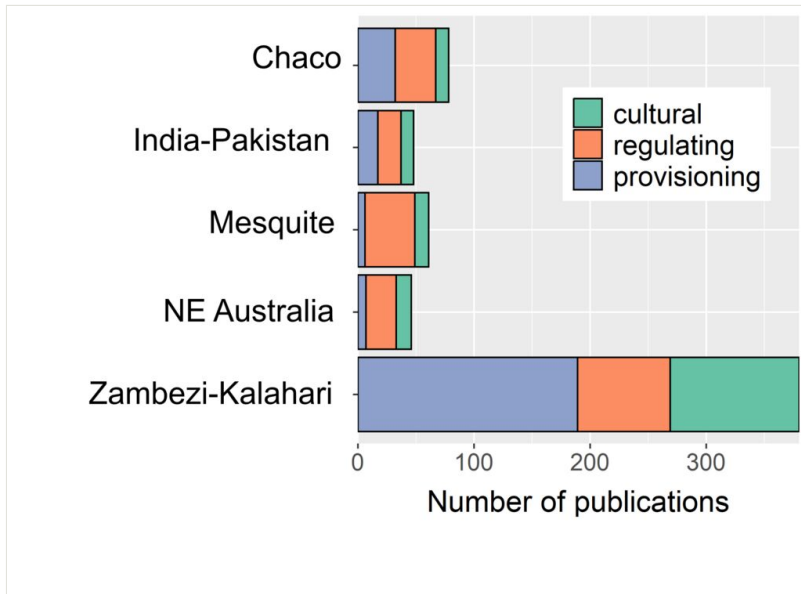


Figure 5. Number of publications of each ES category in the different regions. The maximum value on the x axis exceeds the number of publications because one single publication can include more than one category.

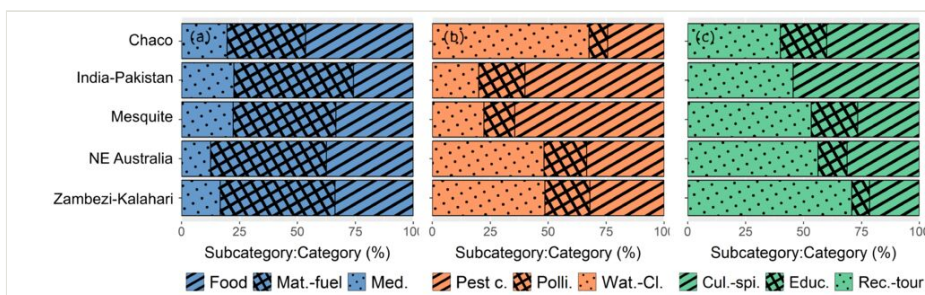


Figure 6. Percentage of publications in each ES subcategory for (a) provisioning, (b) regulating and (c) cultural categories.

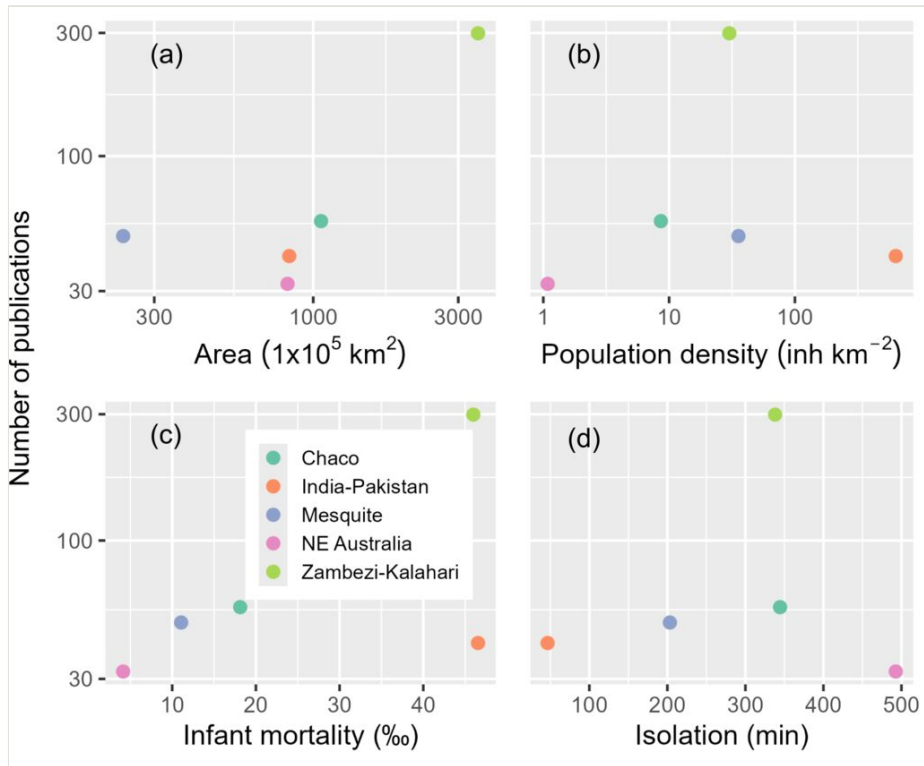


Figure 7.

Number of ES publications in relation to (a) the extent of the study regions and three general traits related to human pressures, i.e. (b) the regional average population density, (c) the regional average infant mortality and (d) the regional average isolation. The relationship of these three last traits and the publication density is depicted in Fig. S2, Suppl. material 2.

Discussion

Globally, bibliometric analyses examining research on ecosystem services have demonstrated a significant increase in publication rates over the past 10 years (Shoyama et al. 2017, Balvanera et al. 2020, Gangahagedara et al. 2021, Liu et al. 2022). This relatively recent development of knowledge in this discipline, compared to other fields such as forest ecology (e.g. the first issue of the Oxford Academic's *Forestry* journal dates from 1927) or invasive species ecology (e.g. the foundational book "The Ecology of Invasions by Animals and Plants" by Elton (1958)), is striking considering its importance for the valuation of nature and human well-being (Mandle et al. 2020). Specifically, for the dry subtropics, our study revealed that the development of ecosystem services science is also recent and that it has experienced considerable growth in the past decade. We acknowledge that this increase in publication rates is well established in global scientific publication records (Bornmann 2015); however, for this subject, we would like to highlight two remarkable facts. First, the number of publications prior to 1990 included in our review

is remarkably low (less than 5%), with no articles published before 1970. This scarce number of older publications is particularly surprising in the case of certain services. For instance, only eleven articles had explored solid fuels, such as charcoal or firewood, prior to 2000, even though rural and urban populations in the Indian subcontinent and Sub-Saharan Africa have long relied on local resources for cooking and heating (Chidumayo 1987, Brouwer and Falcão 2004, Kutsch et al. 2011, Bihari et al. 2013). Secondly, the mention of the term “ecosystem service” has increased significantly after the year 2005.

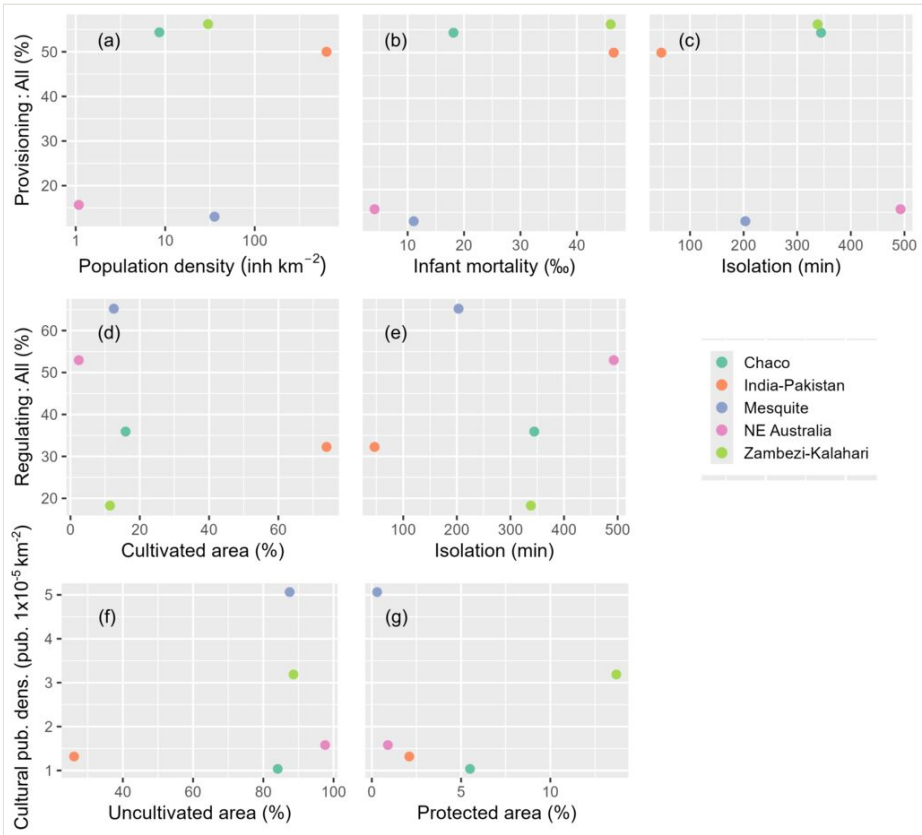


Figure 8.

Relationship between publication representativeness and density (dependent variables) and the human drivers of geographical variability (independent variables). (a-c) Publication representativeness of provisioning ES category; (d-e) Publication representativeness of regulating ES category; (f-g) Publication density of cultural ES category. Only relationships relevant to our predictions are depicted.

Several previous reviews on the subject primarily employed "ecosystem service" as the main search criterion (e.g. Martínez-Harms and Balvanera (2012), Wangai et al. (2016), Nelson et al. (2020)) and restricted their search to articles published in English. Considering this, we wonder whether these previous reviews revealed a recent interest in ecosystem services or if they were reflecting a semantic bias due to the recent adoption of

the term. Another possibility is that this tendency was caused by a general methodological bias, such as including articles published only in English or being influenced by the progressive expansion of scholarly literature databases. In our study, we employed a comprehensive search criterion by encompassing various keywords related to particular ecosystem services (e.g. charcoal products, pollination, tourism, spiritual value). We also considered languages other than English and, in addition to Scopus, utilised the SciELO database, which included a substantial number of references in Spanish and Portuguese. Therefore, based on these criteria, the identified temporal trend indeed reflects a growth in the interest in the concept of ecosystem services. If our search had only used the term 'ecosystem service', the database would have been reduced by 60%, particularly before 2005. Additionally, if we had limited the search to English articles found in Scopus, the database would have been reduced by almost 10%.

We acknowledge that, in science, certain terms can become popular and trigger the development of a certain topic research (Vihervaara et al. 2010). This may have occurred with the term "ecosystem service". It is noteworthy that the concept was developed as early as 1974 by Holdren and Ehrlich (1974) who used in this year the term 'natural services' and that Ehrlich and Mooney (1983) already used "ecosystem service" specifically in their publication in 1983. However, the Millennium Assessment, published in 2005, seems to have played a significant role as milestones for the development of the subject (Fig. 4a), since, after that year, the number of publications mentioning this term increased and became prominent after 2015. This emphasises the significance of how specific topics are named by the scientific community, ultimately influencing international research agendas. The term Nature's Contribution to People -NCP, which builds on the ES concept popularised by the Millennium Assessment (Díaz et al. 2018a, but see Braat (2018)), represents today a complementary view (Peterson et al. 2018) that explicitly recognises that people-nature interaction has to be understood through different cultural lenses. Moreover, a noteworthy concept that has been garnering global attention and also in dry subtropical regions, is Payments for Ecosystem Services (PES) (Vorlaufer et al. 2017) PES aims to evaluate the willingness of beneficiaries of ecosystem services to economically compensate the providers for the service rendered. In our comprehensive review, we observed that 35% of the publications included an economic valuation, although we only considered PES publications with a specific link to certain services (e.g. PES publications concerning carbon sequestration or biodiversity maintenance were excluded). The majority of the publications that incorporated an economic valuation focused on national-level research primarily focused on tourism and recreation. Regrettably, other crucial ecosystem services, such as food and fuel provisioning or pollination, received scarce attention in terms of economic valuation, potentially posing a threat to the long-term sustainability of these essential services.

Our findings also revealed that the distribution of the publications within the dry subtropics is highly heterogeneous, both geographically and thematically. First, regarding the geographic imbalance, we found that their number in Zambezi-Kalahari is almost five times higher than that of the other regions. These results contradict previous works that found few ES publications in Africa (Vihervaara et al. 2010, Costanza et al. 2017), probably due to the

different search criteria used and that they compared Africa's numbers with those from Europe and North America. The over-representation of Zambezi-Kalahari publications may be attributed to the fact that this region constitutes the largest area included in our study. However, it is important to emphasise that neither the extent nor the population density can account for the overall pattern observed in the dry subtropics. For instance, the number of publications in Mesquite, the smallest region, exceeds that of Australia or India-Pakistan (both regions 3.5 times larger). Second, regarding the thematic imbalance, our analysis revealed a predominant focus on publications addressing provisioning ES, whereas regulating and cultural ES received comparably less attention. This pattern contradicts the findings of previous reviews that identified the regulating ES category as the most dominant regionally and globally (Vihervaara et al. 2010, Zhang et al. 2019, Nelson et al. 2020, Gangahagedara et al. 2021), while support others (Schröder et al. 2021). This difference could potentially be attributed to the under-representation of publications from Africa in these other reviews, as studies from North America and Europe tend to dominate the literature (Zhang et al. 2019, Gangahagedara et al. 2021). In the case of our study, the publications exploring provisioning ecosystem services were particularly prevalent in Zambezi-Kalahari. This observation is consistent with the findings of Wangai et al. (2016), who conducted a review specifically focused on Africa and emphasised the significance of provisioning ecosystem services.

In addition to the imbalance amongst the ES categories, we found that only 12% of the publications about ES in the dry subtropics addressed multiple ecosystem services (i.e. more than one ES category), which aligns with the findings of Nelson et al. (2020) in the dry tropical forests of the Caribbean. Even though this percentage increases when we consider only the publications that specifically utilised the term "ecosystem service" (i.e. 18% explored more than one ES category), it still remains quite low. Evaluating ecosystem services in isolation hampers the exploration of synergies, trade-offs and other different forms of interactions (Garibaldi et al. 2018), which may impede the translation of the results into actionable decision-making. Encouraging research that examines multiple categories of ecosystem services would be ideal for enabling the assessment of trade-offs and synergies.

Furthermore, we found that there are also significant biases in the distribution of studies across different subcategories, also leading to unexpected patterns of representativeness. Specifically, the subcategories of medicine, water and climate regulation (fundamentally water), cultural and spiritual and education received limited attention, indicating a relative dearth of research in these topics in DST. Medicine under-representation collides with the strong and old bounds of traditional knowledge on human and domestic animal health in low affluence, isolated areas (Martínez and Barboza 2010, Chinsebu et al. 2014, Khunoana et al. 2019). Water regulation under-representation, only predominant in the regulating category in Chaco, collides with the recurring water deficit in drylands (Noy-Meir 1973, Weltzin et al. 2003). The under-representation of cultural and spiritual topics is particularly striking. Despite the prevalence of this subcategory in India-Pakistan, the number of publications we identified was surprisingly scarce, especially given the extensive and rich history of human occupation and the endogenous moral principles of the Indian

subcontinent (Gadgil and Guha 1992, Dave 2018, Dimri 2022). We also found only a few publications exploring Recreation and tourism and Education simultaneously. This is remarkable considering that these publications were focused on protected areas that commonly are set aside to maintain, amongst other values, both ecosystem services (Paül Carril et al. 2015, Hausmann et al. 2020, Ocelli Pinheiro et al. 2021).

Our assessment did not reveal a distinct relationship between the number of publications and the variables that describe gradients of human pressure. These findings pose a challenge to our hypotheses and predictions regarding the varying perception of ecosystem services along gradients of population density, affluence, isolation from markets and land-cover change. The lack of correlation can be attributed either to:

1. A genuine absence of relationships, meaning that the valuation of the ecosystem services as benefits is independent of the society's link to the natural resources or,
2. A lack of response from the scientific community to a societal interest or need.

There is some evidence indicating that provisioning ES, particularly food, is positively related to population density and that infrastructure plays a role in decoupling the provision and demand of these services through trade and technological advancements (Reader et al. 2022).

Supporting the mismatch between society needs and research, two factors might interplay. First, certain regions receive a particular interest from scientific communities and NGOs; and, second, there are inherent challenges in conducting science in low-resource economies. Regarding the first point, a predominance of Zambezi-Kalahari publications may be related to the fact that Africa represents an attractive point for the global environmental and human well-being agendas and it is under the scrutiny of the international scientific community. Regarding the second point, having a paper published for authors, based in developing countries without international funding, presents inherent difficulties, specifically due to the extremely high costs of journal subscriptions and publication (Creaser and White 2008), which ultimately limits their knowledge dissemination in high quality journals (Gómez-Pompa 2004, Salager-Meyer 2008). This is further exacerbated by disparities in inclusion within editorial and reviewing processes and even by language barriers (Nuñez et al. 2019). Involving local entities (e.g. universities, NGOs, indigenous community representatives) in designing research questions, closely related to their needs, would be a significant step forward.

Supporting the lack of response from the scientific community to a societal interest or need, also two factors might interplay. First, the affiliation of the authors (Stocks et al. 2008, Martin et al. 2012, Wangai et al. 2016). As Wangai et al. (2016) stated, over a half of the first authors of the ecosystem service studies included in their review were affiliated with countries outside of Africa. This external perspective may distort what is considered a necessity or an appreciation of the service by the local population. Second, our study relied on collected data, summarised information and conducted analyses at the regional level, considering factors such as population, percentage of cultivated and protected areas. While this approach would broadly depict the explored relationships, it may not be the most

suitable one due to the potential diversity of cultural and productive contexts within regions. Unfortunately, variables like affluence are not available at a more detailed level. Additionally, the limited number of publications for individual regions further hinders the feasibility of conducting research at a finer spatial level for DST regions, with perhaps the exception of Africa, which may offer more substantial data to explore. The final caveat is that our exploration was limited to publications indexed in Scopus and SciELO, thereby excluding a substantial body of knowledge coming from non-indexed journals, theses and books.

Conclusions

Enhancing our understanding of ecosystem services is imperative for informed decision-making regarding the use of natural resources. Our research highlights that the rapid expansion of ecosystem service studies in the dry subtropics during the past two decades has significant geographical and thematic imbalances. Furthermore, our analysis did not find definitive correlations amongst the number of publications, publication density or their representativeness and the variables utilised as indicators of human pressure. Consequently, this rapid growth does not inherently ensure alignment with local requirements, as it appears to be somewhat detached from the needs of potential beneficiaries. It seems that scientific enquiries into ecosystem services are not solely driven by, directly responsive to, or anticipate societal information needs (Vihervaara et al. 2010). Rather, research efforts appear to be influenced by a variety of factors including national financial and institutional constraints, international research priorities and the individual interests of researchers. These diverse influences contribute to the idiosyncratic nature of this scientific field.

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Author contributions

RA devised the study. RA and GB designed the methods, collected and analysed the data by reviewing and prepared figures and tables. RA wrote the main manuscript text, with contributions from GB.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Appendix 1 - Methodology [doi](#)

Authors: Roxana Aragón, GermánBaldi

Data type: Methodology

Brief description: Scopus and SciELO criteria used to retrieve publications. List of ES categories, subcategories and ES keywords. List of regions' keywords.

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Suppl. material 2: Appendix 1 - Database [doi](#)

Authors: Roxana Aragón, Germán Baldi

Data type: Database

Brief description: Database of the reviewed literature. Besides the reference name and region, eight ecosystem services attributes are depicted: category (provisioning, regulating or cultural), subcategory (as indicated in Table 2), publication language, inclusion of monetary valuation (yes/no), identification of applicant/beneficiary (internal or external to the region), analytical approach (quantitative or qualitative), spatial extent (local, regional or global) and the mention of “ecosystem service” term (yes/no).

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Suppl. material 3: Appendix 2 [doi](#)

Authors: Roxana Aragón, Germán Baldi

Data type: Results

Brief description: Ancillary results.

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Endnotes

- *1 *The numbers correspond to studies that considered economical valuation/total number of publications; or mentioning ES/total number of publications. The denominators include all the publications in each ES category that may exceed the total number of publications given that one publication can study more than one ES category.