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Review Paper

Policy-oriented ecosystem services research on tropical forests in South America: A systematic literature review

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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

Tropical forests are widely recognized for providing valuable ecosystem services (ES), but their existence is increasingly under pressure. The production of policy-relevant ES science is important to effectively convey their value. The main objective of this review is to insight into the associations between scientific knowledge, policy domains and ES categories to identify gaps for advancing further research and improve ES policy-making. For this purpose, we developed a classification system and conducted a systematic review of publications between 2000 and 2020 that focus on the Amazon, Cerrado and Atlantic Forest, the main tropical forest and tropical savannah biomes of South America. The review results indicated high heterogeneity across the biomes. Valuation studies were least prominent in comparison with other categories, whereas descriptive studies dominated ES science in South America. Scientific contributions tended to cluster around central themes of global environmental governance, including GHG emissions. The research peaks and gaps identified for the three biomes can stimulate new knowledge production efforts and inform regionally specific evidence-based policies for enhancing ES programs and policies in South America.

1. Introduction

Scientific research related to the concept of Ecosystem Services (ES) has grown exponentially during the first two decades of the 21st century (Acharya, Maraseni, & Cockfield, 2019; Costanza et al., 2017; Jiang, Wu, & Fu, 2021; Mengist et al., 2020a; Parron et al., 2019; Perevochtchikova et al., 2019). It is now widely recognized that particularly ES preservation in tropical forests is economically important and valuable (Dasgupta, 2021). In the Brazilian Amazon, for example, agriculture and forestry heavily rely on regular rainfall, protection from uncontrolled fire disturbances, pollination services and the abundance of non-timber forest products (NTFPs) (Borges, Brito, Imperatriz-Fonseca, & Giannini, 2020; Leite-Filho, Soares-Filho, Davis, Abrahão, & Börner, 2021; Strand et al., 2018). Communicating these benefits to economic actors and policy-makers is therefore fundamental for the design of policies and programs for ES.

Some ES categories have received more attention in global and national environmental political debates than others. Globally, reducing emissions from deforestation and forest degradation and the role of forests as carbon sink, represented in the acronym 'REDD+', have been promulgated as key climate change mitigation action. In Latin America, biodiversity and hydrological services have received considerable attention in ES studies (Perevochtchikova et al., 2019), while hydrological and water-related services were mostly targeted by PES schemes (Balvanera et al., 2012; Grima, Singh, Smetschka, & Ringhofer, 2016). Water related services, food provision and recreation were also dominant categories in other regions (Malinga, Gordon, Jewitt, & Lindborg, 2015; Mengist et al., 2020a). Considering the full spectrum of different ES (up to 17 according to Costanza et al., 2017), these studies denote a skewed clustering of scientific and political attention to only a few ES

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categories. Similar tendencies were also found in political concepts like the Sustainable Development Goals (SDGs) and the Aichi Targets (Geijzendorffer et al., 2017). Such emphasis on a specific ES categories does not immediately lead to benefits for all categories, especially since "there may be trade-offs between carbon sequestration and the enhancement of other ecosystem services" (Ojea, Loureiro, Alló, & Barrio, 2016, p. 254). To communicate a more complete appreciation of the ES benefits provided by tropical forests, it is useful to better understand these clustering tendencies of policy-relevant ES science.

Enhancing the policy-relevance ES science on tropical forests not only means providing a more complete understanding of ES benefits, but also producing knowledge that is useful for policy-makers. Many conceptualizations of the ES concept highlight the translation of knowledge about biophysical processes that perform certain ecosystem functions into knowledgeable services and benefits that ultimately need to be valued (Haines-Young & Potschin-Young, 2010; Hausknost, Grima, & Singh, 2017; Spangenberg et al., 2014), which Costanza et al. (2017) claim to be "inevitable" for ES conservation. Such valuation, however, is particularly challenging for many ES categories (Small, Munday, & Durance, 2017), often needs to be complemented by integrating scientific and participatory approaches (e.g. Kenter, 2016) and cluster around specific ES categories (e.g. regulating services) rather than others (e.g. cultural services) (Acharya et al., 2019). ES science other than valuation studies is abundant and varies greatly Depending on the ES demand type (e.g. risk reduction, consumption, direct use and preferences; see Wolff, Schulp, & Verburg, 2015) or decision-making process component (Martinez-Harms et al., 2015). In this respect, knowledge production may inform about trade-offs (Howe, Suich, Vira, & Mace, 2014), practical and spatial priorities (Luck et al., 2012; Strand et al., 2018), resource allocation and other forms of, stages in and tools for decision-making processes (Grêt-Regamey, Sirén, Brunner, & Weibel, 2017; Martinez-Harms et al., 2015).

Existing reviews have provided important insights into how ES science has targeted research approaches, ES categories, regions and policy domains (Costanza et al., 2017; Malinga et al., 2015; Mengist et al., 2020a), yet their interrelations are not always clear. Malinga et al. (2015), for example, have mapped the differing importance of ES categories at varying scales and in diverse regions, but do not elucidate, for instance, the policy domains that were associated with them. Perevochtchikova et al. (2019) have addressed the relational aspects to some extent by elaborating the networks established between, among others, research characteristics and ES categories specified per country, but policy domains received much less attention. Making the interrelations between research approaches, ES categories and policy domains more explicit may clarify and enrich our understanding about the status of policy-relevant ES knowledge production and provide a conceptual map for future research efforts. Moreover, it provides policy-makers with guidance on what type of ES knowledge could inform evidence-based policy-making.

In this review paper, we aim to provide a literature review of the diversity of scientific contributions to ES related policy-making. Our main objective is to identify research gaps for policy-relevant ES science, by which we mean the intersection between scientific knowledge production, ES categories and environmental policy-making. In doing so, we also critically discuss the role of scientific knowledge production for ES related policy-making. Our review was conducted for the two largest (sub)tropical rainforest biomes (the Amazon and the Atlantic Forest) and the largest savanna biome (the Cerrado) in South America. The remainder of the paper proceeds as follows. The next section provides a full description of the review methodology. After a brief presentation of the main review results in section 3, we discuss the implications of our results in light of scientific knowledge production and ES policies in section 4 and conclude in section 5.

2. Materials and methods

2.1. Geographical focus

The geographical focus of this literature review involves three South American ecoregions: the Amazon, the Atlantic Forest and the Cerrado (Fig. 1). Due to deforestation dynamics in South America, these ecoregions have lost about 1 million km^2 each, corresponding to 14%, 52% and 81% of historical area, respectively, by 2012 due to land conversion for mainly agricultural purposes (Salazar, Baldi, Hirota, Syktus, & McAlpine, 2015). Due to the still large area of remaining natural vegetation, the Amazon ecoregion has received a lot of attention both nationally and internationally due to its role in climate change mitigation, although it is jeopardized by the perennial threat of deforestation (Lovejoy & Nobre, 2018). In addition, it teems with rich biodiversity and is essential for the maintenance of hydrological and climatic regulation in many regions of South America (van der Ent, Savenije, Schaefli, & Steele-Dunne, 2010). While the Cerrado and Atlantic Forest ecoregions receive much less international attention, their conservation is critical for the few remaining remnants to continue providing ES. Both ecoregions are biodiversity hotspots with a substantial number of endemic species that are currently under threat of forest loss (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). The Cerrado ecoregion in particular is an often overlooked source of essential water regulation services at the local and regional levels, feeding the Paraná-Paraguay, Araguaia-Tocantins and São Francisco watersheds, which concentrate important Brazilian aquifers and hydroelectric plants with great energy potential (Lahsen, Bustamante, & Dalla-Nora, 2016; Latrubesse et al., 2019).

2.2. Search criteria

This literature review followed the PSALSAR (Protocol, Search, AppraisaL, Synthesis, Analysis, Report) methodology, suggested by Mengist et al. (2020b) for research in environmental science, although we acknowledge that other good methodologies are also available (e.g. Higgins et al., 2019). PSALSAR is an extension of SALSA (Search, AppraisaL, Synthesis, and Analysis), a more common approach recommended for literature reviews and meta-analyses (Perevochtchikova et al., 2019) with the objective of increasing the rigor and validity of review results (Grant & Booth, 2009). The use of the PSALSAR rather than SALSA methodology is in line with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009), which we followed in this review.

We applied five search queries in Scopus in order to find the relevant literature for our review, restricting our search to include only the title, abstract and keywords. Although we acknowledge the usefulness of other databases like Scielo and Web of Science, among others, and considering the manual appraisal of each publication, we opted for using only Scopus due to time and budget constraints. All search queries contained three or four components, two of which were held equal for all search queries and involved geographical location and the common focus on forests. The other components focused on variations of ES terminology (query 1, N = 686), different modalities of politics or governance (queries 2–4, N = 3,753) and valuation studies (query 5, N = 975). All queries are reflected below.

Query #1	("amazon" OR "atlantic forest" OR "cerrado" OR "south america" OR "latin america") AND ("forest") AND ("ecosystem service" OR "environmental service" OR "ecological service")
Query #2	("amazon" OR "atlantic forest" OR "cerrado" OR "south america" OR "latin america") AND ("forest") AND ("policy" OR "governance" OR "management") AND ("conservation" OR "protection" OR "natural resource" OR "natural capital")

(continued on next page)

Fig. 1. Geographical location of the Amazon, Cerrado and Atlantic Forest ecoregions.

(*continued*)

Query #3	("amazon" OR "atlantic forest" OR "cerrado" OR "south america" OR "latin america") AND ("forest") AND ("policy" OR "governance" OR "management") AND ("land use")
Query #4	("amazon" OR "atlantic forest" OR "cerrado" OR "south america" OR "latin america") AND ("forest") AND ("policy" OR "governance" OR "management") AND ("sustainable" OR "sustainability")
Query #5	("amazon" OR "atlantic forest" OR "cerrado" OR "south america" OR "latin america") AND ("forest") AND ("value" OR "valuation" OR "price" OR "cost") AND ("ecosystem" OR "nature")

The search was conducted between October 2019 and January 2020 and was amplified and updated between July 2021 and October 2021. From these searches, we downloaded the resulting list of publications between 2000 and 2020 into Excel. All individual lists were merged into a single database (Excel) file. We limited our search to articles published between 2000 and 2020 in order to produce a snapshot of scientific research produced in the last 21 years. Unlike other reviews (e.g. Perevochtchikova et al., 2019), our review objective does not provide a temporal analysis of ES science development, but rather a careful assessment of publications to enable adequate categorization (see next subsection). Finally, categorizing each publication in our database was done manually by reading the abstract, titles and highlights and scanning the paper contents (see below). After excluding duplicate publications as well as non-article publications, these search queries resulted in a total of 4076 publications.

2.3. Inclusion and exclusion criteria

The publications in the database were subjected to several inclusion and exclusion criteria (see Fig. 2). The first exclusion criterion involves the geographical location of the study. In practice, inclusion would primarily occur depending on their relation to at least one of the three ecoregions of interest, namely Amazon, Cerrado and Atlantic Forest. As such, we excluded publications that exclusively studied Chaco dry forests, Chilean coastal forests, Andean mountains or the Brazilian Pantanal, Caatinga and Pampa ecoregions, among others (N = 457). We did not exclude publications that, in addition the three ecoregions of interest, also related to other regions in South America or elsewhere. Secondly, we excluded all publications that did not fit any of the ES subcategories (N = 470) or could not be related to any of the policy domains (N = 1223) as defined in section 3.2. We acknowledge that the latter criterion has a bias. Many of the publications that were excluded

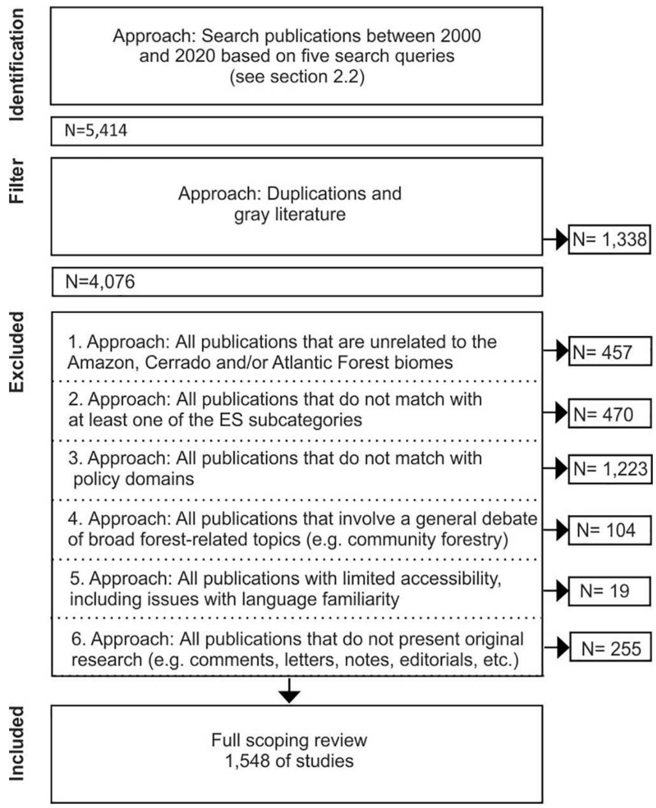

Fig. 2. Exclusion and inclusion criteria (Moher et al., 2009).

from the database, for example, involve conservation practices like reintroduction of key species, assess the conservation status of individual species and similar practices that were not present in our categorical system. Alteratively, some publications mentioned that the research is important for conservation practices and forest management, but failed to specify what this exactly means. The exclusion of these publications from our analysis by no means implies that the studies are unimportant for the conservation of forest ES in general, but merely that they did not clearly fit into at least one of the ES or policy domains defined in section 3.2. Among the remaining publications, finally, we excluded publications that only contribute to a general debate about forest-related topics and were not relevant for the reviewed ecoregions (N = 104), that were inaccessible for various reasons including language issues (i.e. we only selected publications written in English, Portuguese and/or Spanish) (N = 19), or did not present or review original research (N = 255). All excluded publications have been recorded in a separate worksheet (“database exclusion”), while the resulting database (N = 1548) forms the basis for data analysis and synthesis. The full list of publications included in the review can be found in the supplementary material.

2.4. Categorization protocol

The literature review mainly focuses on how the scientific production of ES knowledge relates to policy domains. This objective was operationalized by developing three categorical groups: ES, research approaches and policy domains (see Table 1). The internal structures of these categories, described in further detail below, were thoroughly discussed among the authors and were based on available literature as well as expert knowledge of the authors. The following questions were used as guideline to analyze the interconnections between categorical groups and translate to the categorical and sub-categorical level: (1) which ES were represented by research approaches? (2) to which policy domains were research approaches oriented? (3) which ES were related

Table 1
Categorical structure of the literature review that were used to review the central questions: how does scientific research target policy domains that are relevant for ES conservation and, inversely, how do these policy domains benefit from different research contributions?

Categorical group	Main category	Abbreviation	Sub-category	Bibliographic references
Ecosystem Service	Regulating services	REG	Gas regulation, climate regulation, disturbance regulation, water regulation, erosion control and sediment retention, soil formation, waste management, life cycle maintenance, biological control	Costanza et al., 2017; Czúcz et al., 2018; CICES, v4.3; Millennium Ecosystem Assessment, 2005
	Supporting services	SUPP	Refugia, nutrient cycling	
	Provisioning services	PROV	Food production, raw material production, water supply, genetic resources	
	Cultural services	CULT	Recreational activities, aesthetic values, cultural diversity, knowledge systems, spiritual and religious values, educational values	
Research approach	Descriptive studies	DESC	Ecosystem service indicators, land use dynamics, production processes, policy processes	Martinez-Harms et al., 2015; Czúcz et al., 2018; Malinga et al., 2015; Mengist et al., 2020a; Perevochtchikova et al., 2019
	Prioritization studies	PRIOR	Trade-off analysis, opportunity costs, hotspot identification, cost-benefit analysis	
	Evaluation studies	EVAL	Cost-effectiveness, risk assessment, impact analysis	
	Valuation studies	VAL	Monetary valuation, non-monetary valuation	
Policy domain	Economic instruments	ECON	Market instruments, financial instruments, non-financial instruments	Barton, Benavides, et al., 2017; Barton, Ring, & Rusch, 2017; Scarano et al., 2018; Howlett & Rayner, 2007; Rajão, Soares-Filho, Marcolino, van der Hoff, & Costa, 2014
	Institutional instruments	INSTIT	Protected areas, land programs, zoning	
	Production activities	PROD	Conventional agriculture, alternative agriculture, resource extraction, infrastructure, other activities	
	Regulatory instruments	REGUL	Legal compliance, monitoring, restoration, fire control	
Geographical location	Ecoregions	-	Amazon, Cerrado, Atlantic Forest	Olson et al., 2001; Fontana, Bianchi, & Bennett, 2012; Myers et al., 2000; Seymour & Harris, 2019
	Countries	-	Argentina, Bolivia, Brazil, Colombia, Ecuador, French Guyana, Guyana, Peru, Paraguay, Suriname, Venezuela	

to the policy domains? By extension, we sought to specify these questions for each ecoregion, which leads to the following question: how do the relations between research approaches, policy domains and ES vary across ecoregions and countries?

The first categorical group concerns ES categories (Table 1). Classifications widely vary in the number of ecosystem services identified, but generally involve four categories (Costanza et al., 2017; Czúcz et al., 2018). In order to provide more detail on these categories, we largely followed the 17 ES categories developed by Costanza et al. (1997). Following later developments of the ES concept (Costanza et al., 2017), we complemented these subcategories in two ways based on the subcategorization of cultural services as used in the Millennium Ecosystem Assessment (2005). In addition, we have exchanged the category of pollination for the term life cycle maintenance, as suggested in the Common International Classification for Ecosystem Services (CICES, v4.3) (Czúcz et al., 2018). This resulted in a final categorical group of 21 subcategories.

The second categorical group involves the research approaches with which ES provision by South American forests were studied. The descriptive category (DESC) includes the various scientific approaches that aim to describe the state of ecosystems and their services, the ecological dynamics and processes that influence the capacity of forests to provide theses ES, and the policies and instruments for enhancing or maintaining this capacity. Such knowledge may be particularly useful for problem identification and understanding the social-ecological context (e.g. land use dynamics) within broader decision-making processes (Martinez-Harms et al., 2015). Many review studies have compiled the available knowledge about this category (Czúcz et al., 2018; Malinga et al., 2015; Mengist et al., 2020a; Perevochtchikova et al., 2019). The prioritization category (PRIOR) primarily deals with types of knowledge production that support decision-making processes in the context of alternative scenarios. More specifically, these approaches help to determine whether and where to allocate resources, which regions to address, and which courses of action to choose (Martinez-Harms et al., 2015). The third category contains evaluation studies (EVAL) that address the consequences of specific courses of action, including production activities, forest and land use policies, conservation and restoration practices, and the like, after they have taken place. Evaluation studies also address the risk of diminishing or losing the capacity of forests to provide specific ES. Valuation studies (VAL), finally, are generally divided into monetary valuation and non-monetary valuation studies. Taken together, the research approach categorical group contains 13 subcategories that further specifies the approach adopted by the different lines of research.

Political intervention targets are the focus of the third categorical group, which, in combination, represent the individual components for building an optimal policy mix. Studies on the optimal policy mix for forest, land use and environmental governance vary widely in their classifications. Many scholars distinguish between regulatory mechanisms (e.g. protected areas and restoration), incentive mechanisms (e.g. offsets, compensation and certification) and rights-based approaches, or similar classifications (e.g. access and equity) (Barton et al., 2017a; Barton et al., 2017b; Scarano et al., 2018), although alternatives abound (e.g. Howlett & Rayner, 2007; Rajão, Soares-Filho, Marcolino, van der Hoff, & Costa, 2014). While we acknowledge this variation, we distinguish between four categories that broadly correspond with policy instruments found in South America, particularly Brazil (Rajão et al., 2014). The economic instruments category (ECON) was subdivided into three subcategories, namely market instruments, non-market financial instruments and non-financial economic instruments. We consider production activities (PROD) to be a separate category based on the wide variety of incentives that they may receive, which are not restricted to economic incentives. These categories involve conventional agriculture, alternative agriculture, resource extraction, infrastructure (including urban development) and others. Categories related to government and governance include land tenure and regularization (i.e. protected areas, land programs and zoning; INSTIT) as well as monitoring and control (i.e. legal compliance, monitoring, restoration and fire control; REGUL). As a categorical group, the diversity of policy domains is reflected in 14 subcategories.

The final categorical group, geographical locations, consists of two categories with underlying subcategories. First and foremost, the ecoregion category consists of the Amazon, Cerrado and Atlantic Forest ecoregions. These ecoregions hold the principal areas in the tropical zone of South America (Olson et al., 2001) with singular richness of biodiversity and biomass (Fontana, Bianchi, & Bennett, 2012; Myers et al., 2000) as well as high losses of native vegetation (Seymour & Harris, 2019). Our review also distinguishes between sovereign countries that contain these ecoregions. In the Cerrado and Atlantic Forest ecoregions, the majority of forested areas is located in Brazil, while small patches occur in Bolivia, Paraguay and Argentina. The Amazon ecoregion is also largely located within Brazilian borders, but there are more substantial areas of forest cover in the surrounding countries from east to north.

2.5. Data analysis and synthesis

The final database was analyzed by categorizing each publication according to ecosystem service, methodological approach, policy domain, and geographical location. This categorization was conducted by using a binary scale for publications that were relevant for the respective category (=1) or not (=0) and we allowed for multiple entries within a single category and categorical group. As a consequence, it is important to note that the numeric review results (section 3) reflect a number of relations between two or more categories and, therefore, cannot be compared as higher or lower number of publications. Instead, we refer to contributions rather than publications, accounting for the possibility that individual publications could contribute to multiple categories. In order to diminish biases in the categorization of publications, the construction of the database has been done by six reviewers. Three of these reviewers, together with the lead author and an independent co-author, have been intimately involved in the development of the categorical system. Two other reviewers have received training in assessing publications and making database entries, being able to rely on the metadata. Throughout the process of database construction, the lead author acted as referee in order to settle any issue.

Data analysis and synthesis mainly occurred through the production of heat tables on the basis of the complete database. These tables were produced by using the COUNTIFS function in Excel and were used to visualize all relations between the categorical data (i.e. ecosystem service, methodological approach, domain, and geographical location), which was done by producing heat tables. These heat tables were configurated to highlight (1) the contributions below the 25th percentile (i.e. research gaps, reflected by light shades) and (2) the contributions above the 75th percentile (i.e. “substantial contributions”, reflected by dark shades). In addition to heat tables, we produced a flowchart from the available data in order to visualize (1) the relations between ES categories and research categories, (2) the relations between research approaches and policy domains, and (3) the relations between policy domains and ES categories (Figs. 3-5). Both the heat tables and flowcharts use distinct colors to highlight (i) the relations between ES categories and research approaches (blue), (ii) the relations between research approaches and policy areas (green), and (iii) the relations between policy areas and ES categories (red). Numerical references in the text could therefore be verified by observing the correspondent quadrant color. Using the same data, we also produced tables in order to provide numeric information on the individual flows between these categories.

It is important to stress the differences in representation between heat tables and the flowchart. For reasons of adequate visualization, the latter was produced at the level of categories and reflects a three-dimensional relation, meaning that the contributions of a research

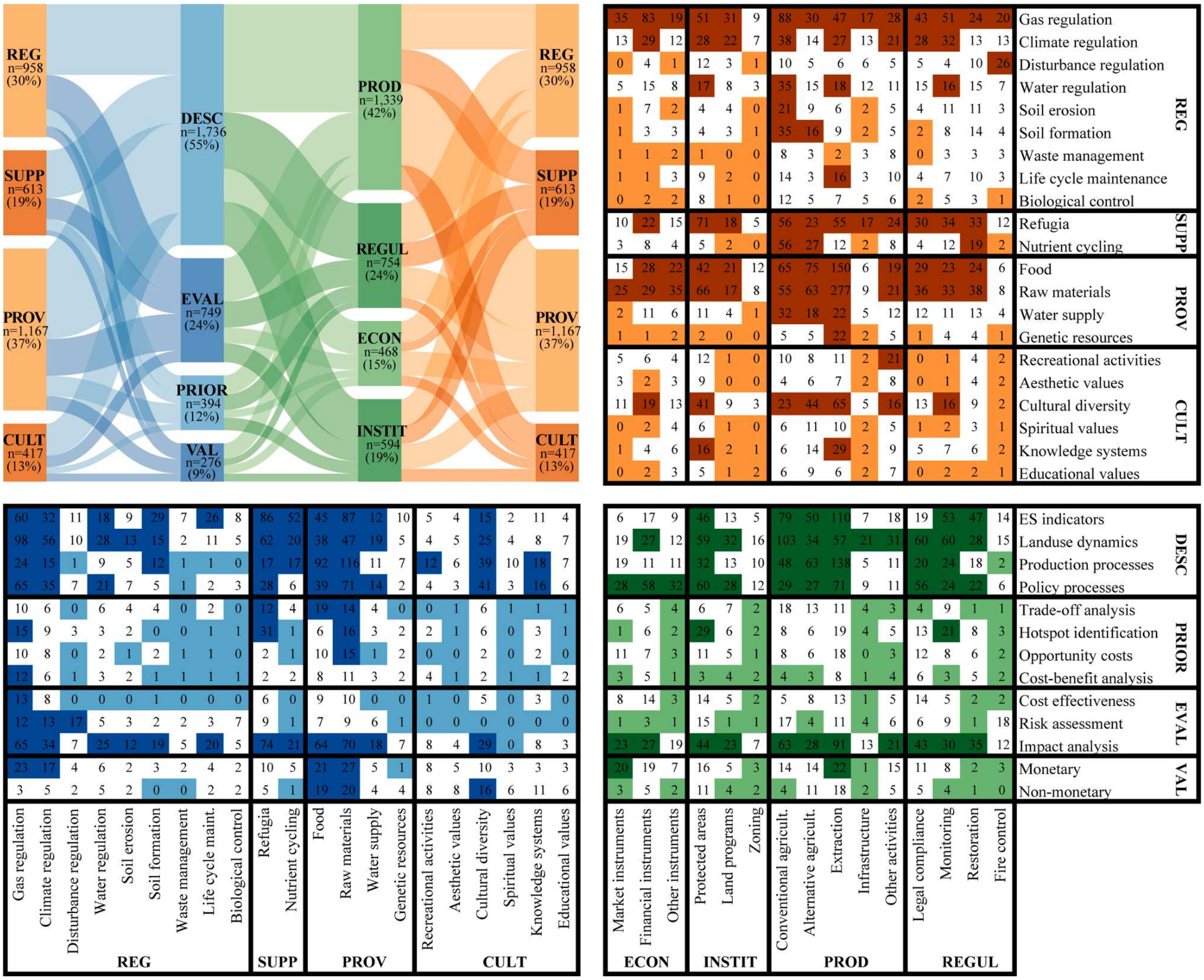

Fig. 3. Research results for the Amazon ecoregion reflecting research contributions at the level of categories (flowchart) and subcategories (heat tables). The different colors represent (i) relations between ES categories and research approaches (blue); (ii) relations between research approaches and policy areas (green); (iii) relations between policy areas and ES categories (red). Within the heat tables, the light shades represent contributions below the 25th percentile (i.e. research gaps), while the dark shades represent contributions above the 75th percentile (i.e. substantial contributions).

approach (e.g. descriptive studies) to an ES category (e.g. supporting services) includes each relation to policy domains (i.e. economic instruments, institutional instruments, economic production and regulatory instruments). By contrast, the heat tables were produced at the level of subcategories and involved a two-dimensional relation, which means that the relation between one type of descriptive studies (e.g. ES indicators) and one type of supporting service (e.g. refugia) does not consider its relations to every single subcategory of policy domains. Although this accounts for differences in total number of contributions and may slightly distort the proportional relations between flowchart and heat tables, the general tendencies remain intact and therefore suitable for visualizing the review results. The presentation of results in section 4 primarily refers to numbers at the sub-categorical level unless otherwise stated.

For reporting the results of our literature review, we followed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines (Moher et al., 2009).These guidelines were integrated into the reporting phase of the PSALSAR framework for environmental science research (Mengist et al., 2020b).

2.6. Limitations

The results of this literature review require some caution with respect to their interpretation. First and foremost, the review only includes peer reviewed literature and is therefore not an adequate reflection of all intricate ways in which the scientific community contributes to ES knowledge. These contributions could occur in written form, such as book chapters, notes, technical papers, doctorate theses, perspective papers and many other forms, but more importantly throughout participation of scientists in policy-making or decision-making processes (e.g. forums, conventions, conferences, round-tables, etc.). Another limitation of our review is that, due to its design, it is not possible to say which stages of the cascade/stairway model most research contributes to. This implies that our results cannot support claims about in what stage of operationalizing this model science is currently advancing. Instead, we focused on categorizing the publications of our database in accordance with categorizations developed by Costanza et al. (2017) and refined with elements from the Millennium Ecosystem Assessment (2005) and CICES (Czúcz et al., 2018). By doing this, we often excluded publications that focused on ecosystem benefits rather than services, such as health and socioeconomic development. At the same time, our approach allows for the possibility that scientific

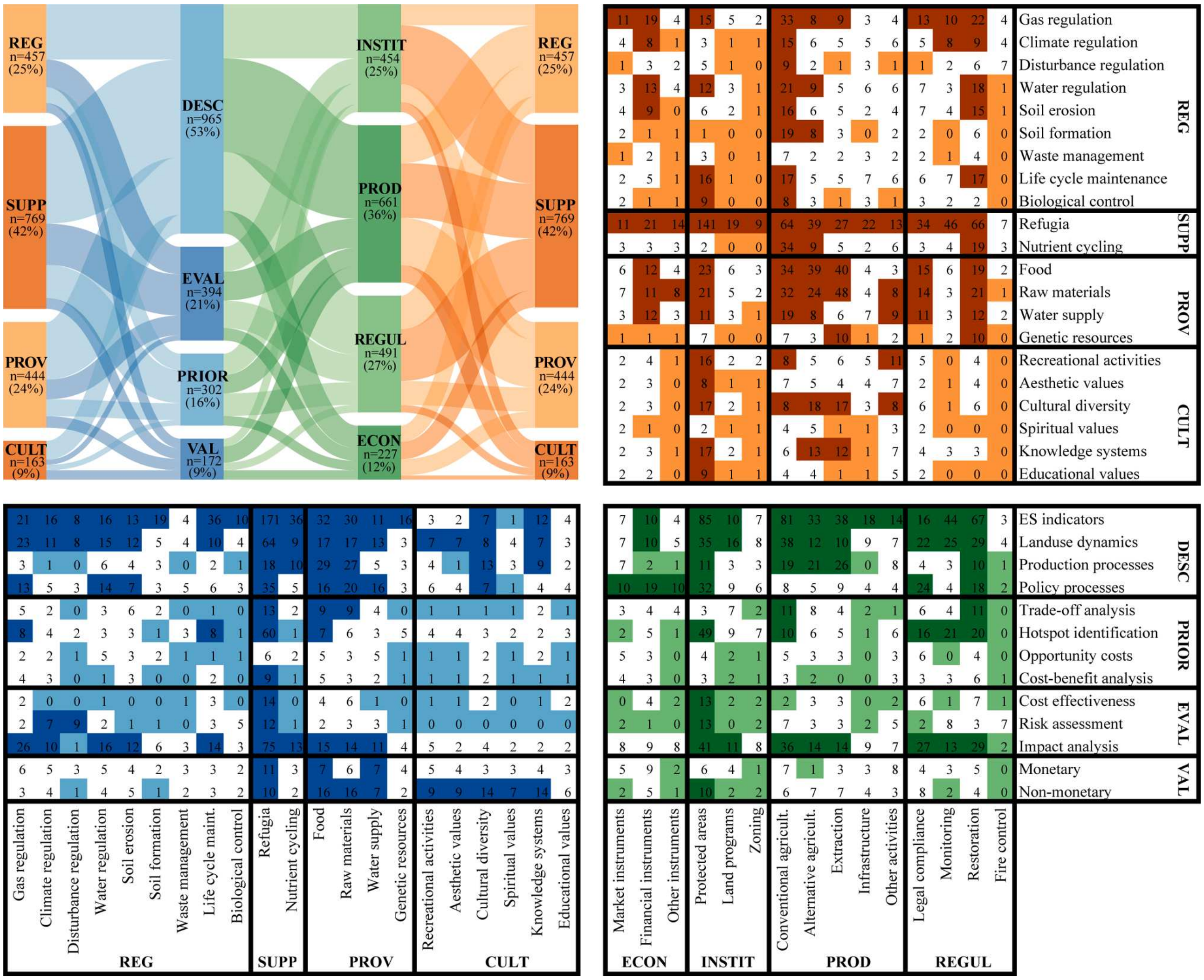

Fig. 4. Research results for the Atlantic Forest ecoregion reflecting research contributions at the level of categories (flowchart) and subcategories (heat tables). The different colors represent (i) relations between ES categories and research approaches (blue); (ii) relations between research approaches and policy areas (green); (iii) relations between policy areas and ES categories (red). Within the heat tables, the light shades represent contributions below the 25th percentile (i.e. research gaps), while the dark shades represent contributions above the 75th percentile (i.e. substantial contributions).

knowledge can contribute in various ways (Martinez-Harms et al., 2015; McKenzie et al., 2014; Posner, McKenzie, & Ricketts, 2016). Finally, the use of publications registered in Scopus limits our analysis to publications predominantly directed at a global audience. Regional databases like Scielo, Redalyc, Latindex and others contain many valuable scientific contributions to ES knowledge that were excluded from the analysis. At the same time, we found that many publications included in the review did represent Brazilian and other South American journals, albeit it may not be fully representative of South American ES science.

3. Results

This section presents the results of the literature review, which reveals both general patterns and specific trends of heterogenous distribution and clustering of ES science contributions in South America. This was observed not only across ecoregions, but also for ES categories, policy domains and research approaches. Research gaps emerge from these patterns and trends. Comparative numbers are presented in Table 2*, while more detailed results per ecoregion are presented in* Figs. 3-5.

Our review results reveal several general patterns that prevail in all ecoregions, clustering around descriptive studies, the Amazon (particularly Brazil). Contributions from descriptive studies (>50%) were most dominant, while valuation contributions (<10%) were least prominent (see Table 2 and Figs. 3-5). This result is expected since a strong set of descriptive studies is a necessary condition for moving towards prioritization, evaluation, and valuation studies. From a spatial perspective, most research studies were concentrated in the Amazon ecoregion (n = 965), followed by the Atlantic Forest (n = 571) and Cerrado (n = 232) ecoregions. Predictably, Brazil was often the research field of most studies reviewed (n = 1272), followed by Peru (n = 187), Bolivia (n = 139), Ecuador (n = 130) and Colombia (n = 102). The other countries surveyed in this review received much less attention (n < 75). At the subcategorical level (Figs. 3-5), all ecoregions reflected a dominant contribution from ES indicators, land use dynamics studies and impact analyses, indicating a predominance of the natural sciences. Among ES subcategories, refugia, gas regulation, food production and raw material provision were commonly among the top contributions. Finally, conventional agriculture and protected areas were mostly associated with in the publications reviewed.

The review results also found patterns that were specific to each ecoregion, indicating regional nuances in relevant policy domains and the ES categories associated with them. The Amazon stands out for its focus on production activities combined with provisional services (see Table 2). More specifically, this could be translated into a strong focus

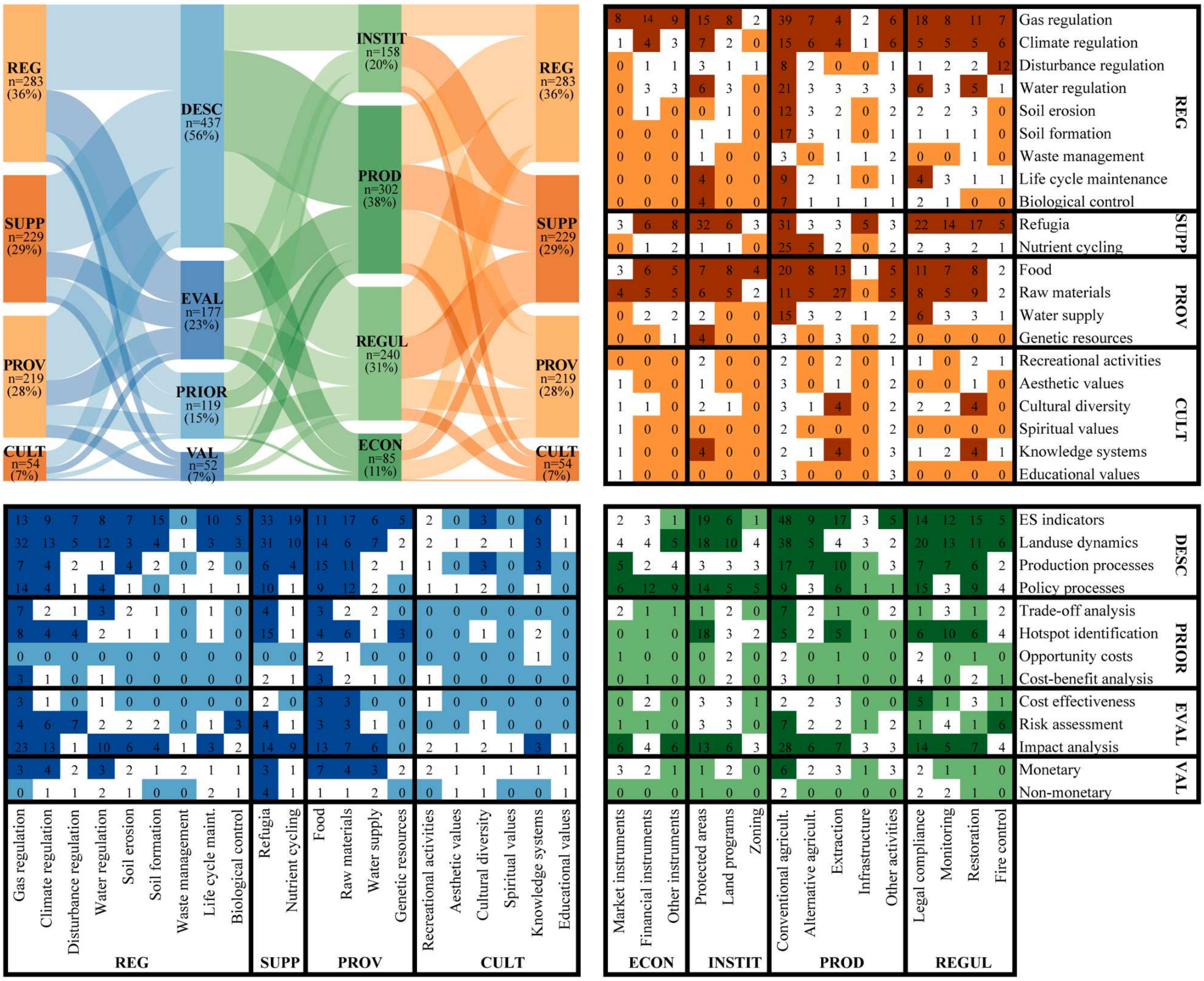

Fig. 5. Research results for the Cerrado ecoregion reflecting research contributions at the level of categories (flowchart) and subcategories (heat tables). The different colors represent (i) relations between ES categories and research approaches (blue); (ii) relations between research approaches and policy areas (green); (iii) relations between policy areas and ES categories (red). Within the heat tables, the light shades represent contributions below the 25th percentile (i.e. research gaps), while the dark shades represent contributions above the 75th percentile (i.e. substantial contributions).

on extraction (n = 587) and conventional agriculture (n = 400), on the one hand, and food (n = 377) and raw materials (n = 513), on the other (see Fig. 3). Specific to this ecoregion, cultural diversity (n = 196) stood out as important among cultural services. The Atlantic Forest could be characterized through contributions to protected areas (n = 305) and restoration (n = 213). The absolute number of contributions to supporting services were even higher than those for the Amazon (769 versus 613, respectively), which diverges from the general pattern (see Table 2). Refugia was by far the most strongly contributed to by the research approaches (n = 498, see Fig. 4). The Cerrado, finally, stood out much less than the (sub)tropical forest biomes. In comparison, it presented a relatively strong focus on conventional agriculture (n = 174) compared with other production activities, as well as a prominent focus on protected areas (n = 94) and legal compliance (n = 93, see Fig. 5).

Clustering of ES science in South America also occurred for associations between ES categories and policy domains, which, like geographical distributions, showed both general patterns and specific tendencies. Comparing Figs. 3-5, some ES categories, most notably refugia, food production, raw material provision and gas regulation, were associated with nearly all policy domains, underscoring their central role in scientific research. Conversely, some policy domains, most notably conventional agriculture in all ecoregions and extraction in the Amazon, were associated with multiple ES categories, suggesting their pivotal role in conserving ES in South America. Most subcategories, however, were found to reflect unique relations. For example, fire control was strongly related to disturbance regulation and (to a lesser degree) gas regulation across the three ecoregions, while soil formation and nutrient cycling were largely linked to agricultural production. By contrast, genetic resources in the Amazon and Atlantic Forest were connected to extraction, while the same ES category in the Cerrado was more strongly related to protected areas.

With very few exceptions, research gaps were found in all ecoregions, policy domains, research approaches and ES categories, which are heterogeneously distributed and further underscore the clustered contributions of ES science described above. The least research contributions were made by valuation studies in all three ecoregions. Although they tended to cover many ES sub-categories, it should be noted that this broad coverage reflects only a few studies. At the sub-categorical level, opportunity cost approaches and non-monetary valuation (except in the Atlantic Forest), for example, were most prone to research gaps, particularly in the Cerrado. To a lesser extent, trade-off analyses also had low number of contributions across ecoregions, although there were some exceptions (see Figs. 3-5). Cultural services have generally received the least number of contributions, although

Table 2
numeric representations of policy-oriented ES research for the Amazon (AMZ), Cerrado (CER) and Atlantic Forest (ATL) ecoregions. The left side reflects numbers of contributions at the categorical level, whereas the right side presents contributions at the sub-categorical level (see section 2.5 for full methodological explanation).

(categorical)	to policy domains: Policy domain	AMZ	CER	ATL	to ES categories: ES category	AMZ	CER	ATL
Descriptive	Economic	240	45	96	Regulating	510	154	233
	Institutional	310	83	228	Supporting	344	138	411
	Production	779	181	393	Provisioning	652	116	242
	Regulation	407	128	248	Cultural	230	29	79
Prioritization	Economic	55	5	40	Regulating	123	41	68
	Institutional	90	33	89	Supporting	80	34	140
	Production	137	31	78	Provisioning	145	35	71
	Regulation	112	50	95	Cultural	46	9	23
Evaluation	Economic	112	24	52	Regulating	248	75	116
	Institutional	137	38	104	Supporting	152	45	173
	Production	311	65	122	Provisioning	266	45	83
	Regulation	189	50	116	Cultural	83	12	22
Valuation	Economic	61	11	39	Regulating	77	13	40
	Institutional	57	4	33	Supporting	37	12	45
	Production	112	25	68	Provisioning	104	23	48
	Regulation	46	12	32	Cultural	58	4	39

(categorical)	from research approach: Research	AMZ	CER	ATL	ES categories: ES category	AMZ	CER	ATL
Economic	Descriptive	240	45	96	Regulating	156	30	68
	Prioritization	55	5	40	Supporting	63	18	73
	Evaluation	112	24	52	Provisioning	175	35	68
	Valuation	61	11	39	Cultural	74	2	18
Institutional	Descriptive	310	83	228	Regulating	194	56	89
	Prioritization	90	33	89	Supporting	129	56	248
	Evaluation	137	38	104	Provisioning	179	35	75
	Valuation	57	4	33	Cultural	92	11	42
Production	Descriptive	779	181	393	Regulating	326	106	159
	Prioritization	137	31	78	Supporting	245	81	230
	Evaluation	311	65	122	Provisioning	589	96	200
	Valuation	112	25	68	Cultural	179	19	72
Regulation	Descriptive	407	128	248	Regulating	282	91	141
	Prioritization	112	50	95	Supporting	176	74	218
	Evaluation	189	50	116	Provisioning	224	53	101
	Valuation	46	12	32	Cultural	72	22	31

(categorical)	research approach: research	AMZ	CER	ATL	policy domain: policy domain	AMZ	CER	ATL
Regulating	Descriptive	510	154	233	Economic	156	30	68
	Prioritization	123	41	68	Institutional	194	56	89
	Evaluation	248	75	116	Production	326	106	159
	Valuation	77	13	40	Regulation	282	91	141
Supporting	Descriptive	344	138	411	Economic	63	18	73
	Prioritization	80	34	140	Institutional	129	56	248
	Evaluation	152	45	173	Production	245	81	230
	Valuation	37	12	45	Regulation	176	74	218
Provisioning	Descriptive	652	116	242	Economic	175	35	68
	Prioritization	145	35	71	Institutional	179	35	75
	Evaluation	266	45	83	Production	589	96	200
	Valuation	104	23	48	Regulation	224	53	101
Cultural	Descriptive	230	29	79	Economic	74	2	18
	Prioritization	46	9	23	Institutional	92	11	42
	Evaluation	83	12	22	Production	179	19	72
	Valuation	58	4	39	Regulation	72	22	31

(Subcategorical)	for policy domains: Policy domain	AMZ	CER	ATL	for ES categories: ES category	AMZ	CER	ATL
Descriptive	Economic	249	57	92	Regulating	652	199	314
	Institutional	326	91	225	Supporting	288	114	348
	Production	922	191	364	Provisioning	615	120	258
	Regulation	468	149	276	Cultural	259	34	123
Prioritization	Economic	54	7	34	Regulating	119	43	83
	Institutional	78	30	90	Supporting	55	24	94
	Production	146	32	76	Provisioning	116	30	68
	Regulation	104	43	101	Cultural	38	5	40
Evaluation	Economic	99	20	34	Regulating	278	95	128
	Institutional	112	35	92	Supporting	111	30	115
	Production	290	68	110	Provisioning	201	39	64
	Regulation	177	52	106	Cultural	61	12	24
Valuation	Economic	56	6	24	Regulating	84	27	58
	Institutional	41	4	25	Supporting	21	9	26
	Production	106	17	49	Provisioning	101	20	65
	Regulation	34	9	26	Cultural	87	10	81

(Subcategorical)	from research approach: Research	AMZ	CER	ATL	for ES categories: ES category	AMZ	CER	ATL
Economic	Descriptive	249	57	92	Regulating	254	48	106
	Prioritization	54	7	34	Supporting	62	20	55
	Evaluation	99	20	34	Provisioning	177	33	69
	Valuation	56	6	24	Cultural	88	6	30
Institutional	Descriptive	326	91	225	Regulating	229	60	89
	Prioritization	78	30	90	Supporting	101	43	171
	Evaluation	112	35	92	Provisioning	184	38	82
	Valuation	41	4	25	Cultural	109	10	85
Production	Descriptive	922	191	364	Regulating	661	206	294
	Prioritization	146	32	76	Supporting	280	79	221
	Evaluation	290	68	110	Provisioning	868	126	308
	Valuation	106	17	49	Cultural	356	41	184
Regulation	Descriptive	468	149	276	Regulating	423	120	199
	Prioritization	104	43	101	Supporting	146	66	182
	Evaluation	177	52	106	Provisioning	247	65	122
	Valuation	34	9	26	Cultural	86	21	43

(Subcategorical)	from research approach: research	AMZ	CER	ATL	for policy domains: policy domain	AMZ	CER	ATL
Regulating	Descriptive	652	199	48	Economic	254	48	106
	Prioritization	119	43	60	Institutional	229	60	89
	Evaluation	278	95	206	Production	661	206	294
	Valuation	84	27	120	Regulation	423	120	199
Supporting	Descriptive	288	114	20	Economic	62	20	55
	Prioritization	55	24	43	Institutional	101	43	171
	Evaluation	111	30	79	Production	280	79	221
	Valuation	21	9	66	Regulation	146	66	182
Provisioning	Descriptive	615	120	33	Economic	177	33	69
	Prioritization	116	30	38	Institutional	184	38	82
	Evaluation	201	39	126	Production	868	126	308
	Valuation	101	20	65	Regulation	247	65	122
Cultural	Descriptive	259	34	6	Economic	88	6	30
	Prioritization	38	5	10	Institutional	109	10	85
	Evaluation	61	12	41	Production	356	41	184
	Valuation	87	10	21	Regulation	86	21	43

variation is again the predominant phenomenon. The Cerrado ecoregion, for example, contains most research gaps in this ES category compared to the other ecoregions, while the Amazon ecoregion has much less (see Table 2). At the sub-categorical level, waste management or spiritual values presented most research gaps. Lastly, economic instruments generally received the least number of contributions from policy-oriented ES research.

4. Discussion: Towards ES-relevant policy-making on tropical forests

The review results indicate that policy-oriented ES research on tropical forests in South America is heterogeneously and unevenly distributed across policy domains and ES categories, indicating tendencies of clusters of ES science contributions and, relatedly, the emergence of research gaps. These results do not contradict the argument by Martinez-Harms et al. (2015) in that different forms of knowledge production can contribute to different stages in decision-making processes, but instead suggests that this production is unevenly spread across ES categories, policy domains and geographic regions.

The identification of research gaps indicates that much work is still necessary to advance policy-relevant ES science in South America. For instance, while the importance of valuing ES is widely advocated (Costanza et al., 2017; Haines-Young & Potschin-Young, 2010; Hausknost et al., 2017; Spangenberg et al., 2014) and the overall number of valuation studies has indeed grown over the past decades (Acharya et al., 2019), the knowledge produced by research approaches other than valuation studies, particularly descriptive studies, are far more abundant, at least in South America. which may attest to the difficulties involved in (monetary) valuation. Some research efforts have attempted to circumvent the complexity of ES valuation by combining other research approaches. The spatially explicit valuation study by Strand et al. (2018), for example, combines valuation with hotspot identification and could provide a format for identifying high value areas that policy-making could prioritize (e.g. through budget allocation or regional action plans). Nonetheless, most policy-relevant ES science focused on South America can still be classified as descriptive, whereas valuation studies, but also prioritization and evaluation studies, are much less pronounced (see section 3.1).

Unsurprisingly, the results strongly correspond with general trends in environmental governance debates. In general terms, our results correspond with a perpetuation of a perceived importance of South American forests in terms of natural resources (Chamberlain, Darr, & Meinhold, 2020), GHG emissions and biodiversity (Droste, Farley, Ring, May, & Ricketts, 2019). Moreover, the revie results also reflect the geopolitical focus on the Brazilian Amazon as both the country with the highest deforestation rates and as most important region for promoting forest conservation in the three ecoregions (see section 3.1). The review results reflect regional trends in land use change dynamics. For instance, the preponderance of contributions to conventional agriculture in the Cerrado may be related to the advance of the agricultural frontier in the region, especially in the Matopiba zone, – an acronym for the states of Maranhão, Tocantins, Piauí, and Bahia – which concentrates the most of the soy expansion in the region (Lahsen et al., 2016; Pires, 2020; Spera, Galford, Coe, Macedo, & Mustard, 2016). The unique scientific knowledge produced for the Amazon corresponds with an emphasis on building a regional bioeconomy (Nobre and Nobre, 2019). By contrast, studies on the Atlantic Forest seem preoccupied with the conservation and restoration of the few remnants left, whereas those directed at the Cerrado may slow down the onslaught of agricultural activities along the Amazon-Cerrado transition zone (Lovejoy & Nobre, 2018). In this respect, the comparatively low number of ES science contributions in the Cerrado is particularly worrisome and perhaps constitutes the main research gap identified in this review.

This clustering of scientific contributions around central themes can overshadow other ES, thus risking a rather narrow operationalization of the ES concept. Our results indicated, for instance, that scientific research efforts on water regulation services, which attracted much attention in ES research in South America (Malinga et al., 2015; Mengist et al., 2020a) and Latin American PES schemes (Grima et al., 2016), did not weigh up to gas regulation services, particularly in the Cerrado ecoregion. A similar phenomenon was also detected in the Amazon ecoregion for research contributions related to climate regulation services underscored by much research (van der Ent et al., 2010). A diversification of research efforts to cover the research gaps identified in this review would be particularly timely as new policies and legislation seek to stimulate, albeit modestly, ES conservation. In Brazilian legislation, for example, instruments like the Environmental Reserve Quota (Law n^{o} 12.651/2012 and decree n^{o} 9.640/2018) or the National PES Program (Law n^{o} 14.119/2021) represent such opportunities (Van der Hoff & Rajão, 2020). Enhancing ES knowledge beyond the central themes of global environmental politics may therefore further enrich such initiatives.

In seeking the diversification of ES science contributions, our review results can be used in various ways to enhance policies that aim to preserve ES provision. As a first step, they can engage in policy domains that present large clusters of ES categories. For instance, cultural services in the Atlantic Forest may particularly benefit from establishing protected areas (Fig. 4), while addressing the negative pressure from conventional agriculture in the Atlantic Forest and Cerrado may enhance regulating services (Figs. 4 and 5). In this respect, our review results could guide the policy-maker to these clusters, from which a deeper understanding about the relations between ES categories and policy domains must be gained. Where ES clustering is weak, secondly, policy-makers may stimulate research projects to fill the knowledge gaps. Thirdly and correspondingly, our review results could build awareness among policy-makers that ES knowledge production is incomplete, for which we advocate the adoption of a precautionary approach to nature conservation. Despite the growing body of ES knowledge, not all trade-offs have been made visible due to research gaps (see section 3.4). To mitigate this issue, fourthly, policy-makers could draw on sources of knowledge other than science, including lay and indigenous knowledge, particularly with respect to cultural services. As mentioned in the introduction, some scholars have already observed the increasing application of integrated models and participatory knowledge production, including valuation, that are promising for addressing knowledge gaps (Costanza et al., 2017; Kenter, 2016). Finally, policy-makers can use the insights of the review results to design a governance framework that is premised on regional necessities and potential.

Our review offers an alternative kind of map for identifying knowledge gaps that complements other literature reviews conducted for South American ecosystems (Balvanera et al., 2012; Grima et al., 2016; Malinga et al., 2015; Perevochtchikova et al., 2019). As such, it is our hope to stimulate new research efforts directed at ES other than the central themes described above in order to engender more pathways towards forest conservation. Such effects may be stimulated domestically through jurisdictional approaches to building a sustainable development model for tropical forests (e.g. Di Gregorio, Massarella, Schroeder, Brockhaus, & Pham, 2020) or internationally through the growing efforts to restrict trade of commodities linked to (illegal) deforestation (e.g. Schilling-Vacaflor & Lenschow, 2021). To use the alterative map presented here to address research gaps in a way that impacts policy-making, it is advisable that research groups and organizations, domestic or foreign, do so with an emphasis on policy-relevance for producing new ES knowledge. This may mean collaboration or co-production with national or subnational jurisdictions to ensure the political utility of the ES knowledge, but may also involve building participatory approaches to complement scientific knowledge production (Kenter, 2016).

5. Concluding remarks

This literature review contributed to the identification of research gaps in policy-oriented science for ES of tropical forests in South America. These insights could be useful for policy-makers to understand where scientific research has most contributed to and which elements require either further scrutiny or alternative forms of knowledge production. In a similar fashion, our results are useful for defenders of nature conservation as a roadmap for advocating policy reforms and conservation initiatives, particularly in areas (e.g. zoning, waste disposal) where such policies are scarce. Finally, this review provides insights for the scientific community that enhances the understanding of how their efforts contribute to policy-oriented ES knowledge. It is unlikely that knowledge production alone may overcome political biases and economic interests that systematically undermine the public good in favor of the gains of specific groups. But even though scientific knowledge is not sufficient, it certainly is a key ingredient for the creation of better policies for ES conservation in tropical forests.

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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