Sustainability Science (2022) 17:105–119
https://doi.org/10.1007/s11625-021-01049-z

ORIGINAL ARTICLE

A novel ecosystem (dis)service cascade model to navigate sustainability problems and its application in a changing agricultural landscape in Brazil

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Received: 8 May 2021 / Accepted: 23 September 2021 / Published online: 11 October 2021

Abstract

The ecosystem service framework has been instrumental in navigating local to global sustainability issues. Yet as ecosystem services (ES) focus on nature's positive contributions to people, some have argued that 'ecosystem disservices' (EDS), or nature's negative contributions, should also be taken into account to better orient sustainability policies. However, joint ES and EDS assessments remain rare in sustainability research, partly because of the persisting conceptual ambiguity around the EDS concept. This study aimed to develop these joint assessments and test their relevance in addressing sustainability issues. To this end, we devised a novel cascade model that helps to define ES and EDS in a multi-level context that considers both as coproduced by ecosystems and people. In order to explore the potential and limitations of this model, we then applied it in a Brazilian landscape where reconciling agriculture and forest conservation is a critical sustainability challenge. Using the model in comprehensive interviews with farmers about their perceptions and management practices of forests, we found that they had an overall positive valuation of forests, but identified both positive and negative interactions between forests and farms at different organizational levels. The model also revealed a vicious circle between crop expansion, a resulting decrease in certain ES and an increase in certain EDS, which might exacerbate tensions between agriculture and forest conservation in the future. Additionally, the model allowed a window on the diverse preventive and regulating practices that the interviewed farmers have adopted to cope with increasing EDS without necessarily harming biodiversity. Based on this case study, this novel cascade model seems a promising conceptual tool to uncover the interactions between ES and EDS, opening new research and policy avenues to support sustainability.

Keywords Cerrado · Conceptual framework · Coproduction of ecosystem services · Forest conservation · Nature's contributions to people · Socio-cultural valuation

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Introduction

The ecosystem service (ES) concept has received considerable attention in recent decades from both the scientific and political spheres dealing with environmental issues. Initially, ES had an educative function (i.e. raising awareness of how humans depend on ecosystems), and progressively acquired a scientific function (i.e. improving the understanding of social-ecological systems) as well as a decision-support function (Norgaard 2010; Ainscough et al. 2019). The concept's multi-faceted use means that ES have multiple, sometimes competing, meanings, which has resulted in a range of conceptual frameworks, perspectives, and debates (Fisher et al. 2009; Schröter et al. 2014; Barnaud and Antona 2014; Díaz et al. 2018). This lack of unified understanding can hinder the clarity of the ES concept, which is a key concern in certain research such as environmental accounting (Boyd and Banzhaf 2007; Potschin and Haines-Young 2011). Yet this ambiguity can also allow ES to play the role of a boundary object that facilitates dialogue between academic disciplines and stakeholders (Star and Griesemer 1989; Ainscough et al. 2019). As a consequence, ES definitions have constantly navigated between rigidity and flexibility with the dual aim of providing robust and comparable ES assessments across case studies (Fisher et al. 2009) while embracing different worldviews and perspectives (Díaz et al. 2018).

In terms of these objectives, one of the controversies around the ES concept has been its capacity (or incapacity) to take into account negative impacts on human well-being by ecological entities and processes (Lyytimäki and Sipilä 2009; Shackleton et al. 2016). Over a decade ago, the concern was raised that ecosystems should not only be considered as a source of services and benefits, but also as a source of 'disservices' and costs due to zoonotic diseases, crop raiding by wildlife, carnivore predation on humans and livestock, etc. (McCauley 2006; Dunn 2010). Since then, the 'ecosystem disservice' (EDS) concept has been discussed in many opinion papers (e.g. Lyytimäki and Sipilä 2009; Shapiro and Báldi 2014; Lyytimäki 2015), with repeated calls for joint ES–EDS assessments in order to better understand the complex links between ecosystems and human well-being with the aim of improving sustainability policies (Schaubroeck 2017; Blanco et al. 2020a).

Despite this, studies that account for both ES and EDS remain rare (Blanco et al. 2019a), which is partly due to a twofold conceptual ambiguity around the EDS concept (Von Döhren and Haase 2015; Saunders 2020). First, there is no consensus on the delineation between EDS and the detriments they produce. Some effectively understand EDS as the subset of ecological functions that have actual or perceived negative impacts on human well-being (e.g. Lyytimäki and Sipilä 2009; Shackleton et al. 2016), while others use EDS to refer to the negative impacts and costs themselves, caused by ecological functions (e.g. Escobedo et al. 2011; Huang et al. 2015). This ambiguity blurs EDS valuation studies. For example, when a wild animal raids crops, what exactly should be assessed as the EDS: the animal eating the crops, which would be approximated by the probability that the animal visits the field; the amount of crops eaten, which would be assessed by the yield loss due to raiding; or the cost associated with this crop loss, which would be evaluated by the farmer's income loss? Second, it is still unclear how EDS can be accurately assessed with ES in a standardized operational framework. While several ES and EDS frameworks have been proposed (e.g. Zhang et al. 2007; Power 2010; Ma et al. 2015; Barot et al. 2017; Vaz et al. 2017; Campagne et al. 2018; Vialatte et al. 2019), they all remain elusive on how EDS interact with ES and how this interaction impacts different stakeholders' well-being, generating environmental justice and equity issues. We started from the hypothesis that a key step to address these conceptual challenges and foster integrated approaches in sustainability science would be to incorporate the EDS concept into the most seminal ES framework: the cascade model (Saarikoski et al. 2015; Costanza et al. 2017).

The central objective of this study was to conceptually clarify EDS and devise a novel framework that combines the concepts of ES and EDS—hereafter, E(D)S—then apply this in a case study to test its potential and limitations in finding innovative pathways to sustainability. In a first step, we developed an E(D)S cascade model that offers a non-ambiguous joint ES–EDS assessment working from the assumption that services and disservices are coproduced by ecosystems and people. In a second step, we conducted a qualitative E(D)S socio-cultural valuation study using the E(D)S cascade model in the Cerrado Biome in Brazil, a region where current agricultural dynamics and forest and biodiversity conservation initiatives raise significant socio-environmental challenges. To help find pathways to sustainability in this context, we explored how farmers perceived and managed the forested areas of their farms through an E(D)S lens. This allowed us to test the potential and limitations of the model in the context of our case study, which in turn highlighted some global key research questions for sustainability science that an integrated ES and EDS approach could help address.

The E(D)S cascade model

Defining ecosystem services and disservices

The concepts of E(D)S have been diversely defined (see Table S1), but two features appear consensual in the literature. First, E(D)S are social constructs: they do not exist independently from humans per se (in contrast to ecological structures, functions and processes), but are subjective interpretations, socially situated and constructed, of ecological phenomena (Fisher et al. 2009; Harrington et al. 2010; Spangenberg et al. 2014). A given ecological phenomenon can, therefore, be valued as positive (i.e. an ES) or negative (i.e. an EDS) depending on the context or person (Lyytimäki and Sipilä 2009). Second, the link between a specific E(D)S and human well-being can be direct or indirect, leading to a distinction between intermediate and final E(D)S that also depends on the context and the person (Fisher et al. 2009; Landers and Nahlik 2013; Haines-Young and Potschin 2018). For example, water quality is a final ES when water is used for drinking, but an intermediate ES when it supports fish populations for angling (Fisher et al. 2009).

Drawing on these considerations, we defined ES as *the ecological structures, functions and processes that people recognize as supporting, directly or indirectly, their well-being*. This definition implies that ES (i) must be ecological phenomena, (ii) must be viewed as positive by a person or a group of people, and (iii) can be either intermediate or final. Symmetrically, we defined EDS as *the ecological structures, functions and processes that people recognize as detrimental, directly or indirectly, to their well-being*. Following this definition, EDS (i) must be ecological phenomena, (ii) must be viewed as negative by a person or a group of people, and (iii) can be either intermediate or final. Intermediate EDS can be manifested through either a negative effect on an ES (e.g. crop raiding negatively affecting crop production) or a positive effect on another EDS (e.g. the spread of an invasive species can reinforce wildfire occurrence; de Wit et al. 2001). In contrast, final EDS have a direct impact on human well-being (e.g. wild animal attacks on humans, pollen allergens).

Ecosystem services and disservices in the cascade model

Figure 1 presents the novel E(D)S cascade model illustrated through the case of a landscape where 'natural' habitats interact with human-modified habitats, such as an agricultural landscape, and where a broad range of intermediate and final E(D)S are delivered. The E(D)S cascade model is based on the following five key aspects:

(1) *E(D)S are a subset of ecological structures and functions*. Multiple ecological interactions and feedbacks occur within ecosystems at different organizational levels, E(D)S being those that are acknowledged as positive or negative by some individuals or groups. Of these, intermediate E(D)S influence *ecological receivers* (i.e. other ecological structures and functions) that are themselves positively or negatively valued by people, whereas final E(D)S influence *human receivers*, i.e. people who directly benefit or suffer from them.

(2) *E(D)S are delivered at different organizational levels*. E(D)S are provided by different *ecological providers* at different organizational levels (Saarikoski et al. 2015). For example, crop raiding is done by specific species, whereas erosion control relies on larger ecological units, and scenic beauty depends on a particular landscape configuration and composition.

(3) *E(D)S generate material and non-material benefits and detriments*. The model explicitly distinguishes E(D)S from the benefits and detriments they induce, even though this distinction is not always straightforward (Potschin-Young et al. 2018). In our definition, E(D)S are ecological phenomena, and benefits and detriments are the point at which human welfare is directly affected by them (Fisher et al. 2009). For example, forests (a provider) provide harvestable timber (an ES) that can then be processed to build fences, houses or furniture (benefits).

(4) *E(D)S are joint products*. An ecological provider can simultaneously deliver several E(D)S to different receivers. For example, a tree can provide shelter to a reared animal, compete with crops for light and nutrients, contribute to soil fertilization, while representing a risk to animal and human safety or property when it falls (Blanco et al. 2020b). Furthermore, a discrete ES or EDS can lead to several benefits or detriments. For example, predator attacks on humans (an EDS) can generate physical injuries as well as a feeling of insecurity (two different detriments).

(5) *E(D)S are coproduced by ecosystems and people*. Acknowledging recent conceptual advances (Spangenberg et al. 2014; Palomo et al. 2016; Fischer and Eastwood 2016), the model considers that humans participate in the production of E(D)S through physical and cognitive processes, including the multiple values people assign to ecological phenomena. For example, a landscape or a forest is not beautiful per se, but it can be cognitively interpreted as such by people in a certain historical and cultural context.

The design aim of the E(D)S cascade model was to offer both robustness and flexibility: clarifying E(D)S in a robust conceptual model in which services and disservices can be jointly assessed, while leaving room for people's subjectivity about the values they assign—positive or negative—to ecosystem-based outcomes.

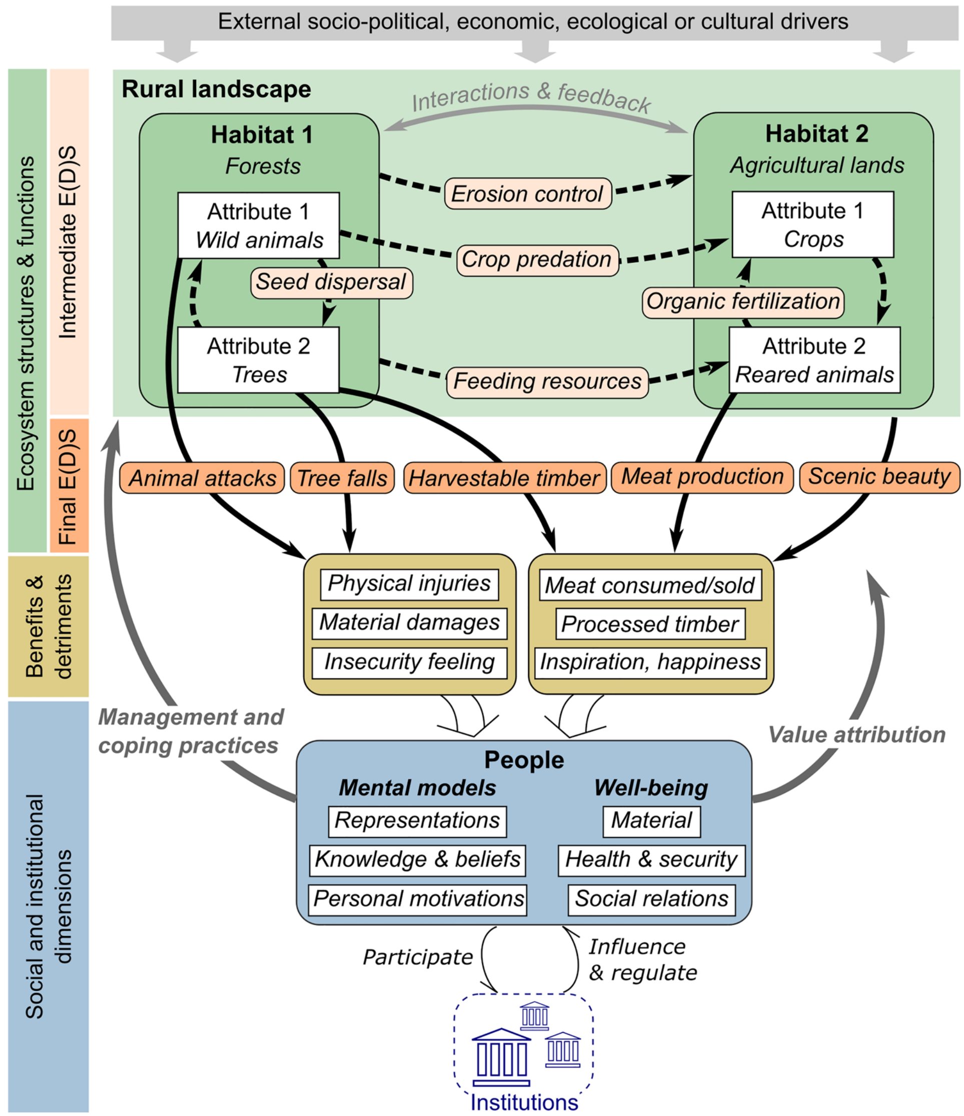

Fig. 1 Ecosystem (dis)service cascade model illustrated in a typical rural landscape composed of forested and agricultural areas. Flows of intermediate E(D)S are shown as dotted black arrows; flows of final E(D)S are shown as solid black arrows

Methods

Case study area

The E(D)S cascade model was applied in a case study in the Mato Grosso do Sul state in Brazil, at the border of the Serra da Bodoquena National Park. This area lies within the Cerrado legal biome, but ecologically speaking is on the boundary of two major ecological formations, the Cerrado and the Atlantic Forest (Fig. S1). With its high levels of biodiversity and endemic species, the region is a biodiversity hotspot (Myers et al. 2000; Sabino and Andrade 2003; Koroiva et al. 2017). At the same time, it is a frontline for agricultural pioneers, the first of which principally created zebu cattle ranches with extensive planted pastures, expanding in the last decades into soy/maize cropping systems (Franco 2001). As a result of crop expansion, the region and its national park face both an ecological and a socio-economic challenge as the region is an important site for ecotourism, which relies on its unique ecosystems and natural attractions (Sabino and Andrade 2003).

To promote the sustainable coexistence of agriculture and biodiversity in the region, all rural properties must comply with the Brazilian Forest Code. In the Cerrado biome, this code requires rural landowners to maintain natural vegetation in Legal Reserves on 20% of their property and to preserve sensitive ecosystems by delimiting Areas of Permanent Protection on mountains, steep grades, hilltops, ridges, and around watercourses and reservoirs (Machado 2016). In their remaining lands, rural landowners are allowed to cut 10–20 m^3 of wood per year (depending on the tree species) for self-consumption (e.g. firewood, fences, buildings), but must obtain a license to cut down larger volumes of wood (e.g. to convert a forest into a pasture or to remove scattered trees from a pasture).

As a consequence, rural forests, which encompass all the woody elements managed by farmers such as farmland forest patches, hedgerows, isolated trees and copses (Genin et al. 2013; Blanco et al. 2019b), are substantial components of the farms in the region and play an important ecological and socio-economic role (Godoi et al. 2018). In a context of increasing tension between biodiversity conservation and crop expansion in the area, understanding how these farmers perceive and value rural forests as potential sources of E(D)S is therefore vital in finding pathways toward more sustainable agricultural landscapes.

Data collection

To understand farmers' perceptions of the different E(D)S associated with rural forests, we conducted semi-structured interviews at a total of 45 farms between June and July 2019. Visited farms were selected through a purposive sampling method aimed at including diverse types of farming systems rather than having a statistically balanced sample. Depending on availability and willingness to participate, at least one interview per farm was conducted with the landowner or a manager (hereafter indistinctly referred to as farmers).

The first part of each interview was structured with closed-ended questions in order to collect systematic data about farm and farming system characteristics, such as the farm surface area, the different types of crops grown or the number of head of cattle. This information was not analyzed in the study, but allowed us to ensure that our sample represented a range of farms and farmers' profiles.

The second part of each interview had a looser structure and was conducted as a discussion to enable an in-depth qualitative analysis (Russell 2011). The discussion was oriented by an interview guide that included a list of predefined questions aimed at revealing farmers' perceptions and management practices of the multiple E(D)S associated with rural forests (see S1. Interview guidelines). In particular, farmers were asked about the benefits and detriments of having forests on their farms, how they used forests (e.g. for medicinal purposes, for firewood supply, etc.), and the utility and constraints of other trees they had on their farms (e.g. isolated trees in pasture areas). Respondents were not presented with the specific concepts of E(D)S during interviews: we used common terms such as benefits, advantages, detriments and drawbacks to formulate the questions and extend the discussions. This allowed us to collect respondents' perceptions and opinions based on their own terms, rather than from a predefined list of E(D)S. This loose interview strategy also allowed interviewers to adapt to respondents: for example, by inviting them to further elaborate on specific topics that inductively appeared important to them during the conversation.

The interviews were conducted in Portuguese by groups of three to four graduate and undergraduate students from France and Brazil: all were recorded and transcribed. The research was approved by the ethics committee of the Federal University of Mato Grosso do Sul (CAAE: 87336418.6.0000.0021; approval number: 3.587.104).

Ecosystem (dis)service identification and analyses

After collecting the interview data, we analyzed it through a mixed method relying primarily on an in-depth qualitative analysis and secondarily on quantitative treatments. First, all interview transcripts were imported into NVivo (QSR International Pty Ltd. 2021), a computer-assisted qualitative data analysis software that we used to encode interviews, identifying the occurrence of the themes covered in each interview in order to group them and draw insights from them (see Fig. S2 for the final coding scheme). We encoded all references as a service or disservice and inductively ordered them into categories. For ES, we used the Common International Classification of Ecosystem Services (CICES v5.1), which provides pre-identified ES categories as well as the possibility to add ad-hoc categories (Haines-Young and Potschin 2018). For EDS, due to the absence of a broadly accepted classification, we designed ad-hoc EDS categories and types based on existing studies (Shackleton et al. 2016; Blanco et al. 2020b). For each reported E(D)S, we also identified the ecological provider and receiver mentioned (or implied) by informants, and whether it was final (i.e. directly affecting humans) or intermediate (i.e. affecting another ecological feature). Finally, we encoded information about rural forest management practices and farmers' strategies in dealing with EDS.

Second, to complement this qualitative analysis, we built a database that pooled together all occurrences of the E(D)S cited by farmers and imported this into the R environment (R Core Team 2018). We used this to produce a Sankey diagram with the 'networkD3' package (Allaire et al. 2017) to visualize the main flows of E(D)S from ecological providers to social and/or ecological receivers as reported by respondents.

Results

Farmers' perspectives on E(D)S associated with rural forests

A total of 30 ES and 18 EDS associated with rural forests were identified from our interviews with farmers, including 15 final and 15 intermediate ES, and 6 final and 12 intermediate EDS (Table 1). At an individual level, each farmer mentioned an average of 4.1 ES (±2.3 SD) and 1.9

Table 1 List of the ecosystem services (ES) and disservices (EDS) identified from interviews conducted on 45 farms in Mato Grosso do Sul, Brazil

E(D)S class code	E(D)S class	E(D)S	Type of E(D)S	N¶
Provisioning ES: 8 ES identified within 5 different classes				
S1.1.5.1	Wild and domesticated plants used for nutritional purposes	Harvestable fruits	Final	14
		Edible wild plants (incl. mushrooms)	Final	3
S1.1.5.2	Fibers and other materials from wild plants for direct use or processing	Harvestable timber	Final	25
		Medicinal plants	Final	4
		Handcrafting materials	Final	1
S1.1.5.3	Wild plants used as a source of energy	Harvestable firewood	Final	7
S1.1.6.1	Wild animals used for nutritional purposes	Edible wild animals	Final	4
S1.2.1.1	Seeds, spores and other plant materials collected for maintaining or establishing a population	Harvestable seeds	Intermediate	1
Regulating and maintenance ES: 16 ES identified within 11 different classes				
S2.2.1.1	Control of erosion rates	Prevention and reduction of soil erosion	Intermediate	8
S2.2.1.3	Hydrological cycle and water flow regulation	Maintenance of water sources	Intermediate	1
S2.2.1.4	Wind protection	Windbreak effect	Intermediate	2
S2.2.2.3	Maintaining nursery populations and habitats	Habitat and feeding resources for reared animals	Intermediate	15
		Habitat and feeding resources for wildlife	Intermediate	3
S2.2.3.1	Pest control	Pest and predator control	Intermediate	3
S2.2.3.2	Disease control	Disease and parasite control	Intermediate	1
S2.2.4.1	Weathering processes and their effect on soil quality	Maintenance of soil moisture	Intermediate	2
		Physical decompaction of soils	Intermediate	1
S2.2.4.2	Decomposition and fixing processes and their effect on soil quality	Decomposition of plant residue	Intermediate	2
S2.2.5.1	Regulation of the chemical condition of freshwaters by living processes	Maintenance of river quality	Intermediate	2
S2.2.5.2	Regulation of the chemical composition of the atmosphere and oceans	Mitigation of air pollution	Final	1
S2.2.6.2	Regulation of temperature and humidity	Sheltering effect for reared animals	Intermediate	32
		Maintenance of air humidity	Intermediate	2
		Sheltering effect for planted crops and pastures	Intermediate	1
		Sheltering effect for humans	Final	1
Cultural ES: 6 ES identified within 4 different classes				
S3.1.1.1	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Opportunities for nature-based tourism	Final	8
		Opportunities for angling	Final	4
S3.1.1.2	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	Opportunities for walks and observations	Final	5
		Overall natural beauty	Final	5
S3.1.2.1	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	Habitats, plants and animals of special interest	Final	3
S3.2.2.1	Characteristics or features of living systems that have an existence value	Existence value of natural ecosystems	Final	3
Material EDS: 3 EDS identified within 3 different classes				
D1.1	Impact on buildings	Risk of damage to buildings	Final	1
D1.2	Impact on material assets	Risk of damage to fences	Final	2
D1.3	Raiding by wild animals	Animals stealing food from houses	Final	1
Indirect EDS: 12 EDS identified within 5 different classes				
D2.1.1	Causes of reduced terrestrial plants grown for nutritional purposes	Raiding of cultivated crops	Intermediate	27
		Weed dissemination and development into agricultural areas	Intermediate	2
		Raiding of edible fruits	Intermediate	1

Table 1 (continued)

E(D)S class code	E(D)S class	E(D)S	Type of E(D)S	N[¶]
D2.1.2	Causes of reduced animals reared for nutritional purposes	Predation on reared animals	Intermediate	30
		Competition with reared animals for feeding resources	Intermediate	3
		Disease and parasite transmission to reared animals	Intermediate	1
		Risk of tree falls on reared animals	Intermediate	1
		Unsuitable habitat conditions for reared animals	Intermediate	1
D2.1.3	Uncontrolled crossbreeding between wild and domestic animals	Crossing of boars with domestic pigs	Intermediate	2
D2.1.4	Reduced potential of productive habitats	Degradation of agricultural soils by wildlife	Intermediate	2
		Physical obstacles to agricultural machinery	Intermediate	1
D2.2.1	Negative impact on hydrological cycle and water flow	Reduction of water sources	Intermediate	1
Health and security EDS: 3 EDS identified within two different classes				
D3.1	Dangerous physical contacts	Animal attacks on people	Final	2
		Animals causing traffic accidents	Final	1
D3.2	Disease and parasite transmission	Zoonotic disease transmission to humans	Final	1

The ES were classified into three sections and 19 classes based on the CICES v5.1 (Haines-Young and Potschin 2018) and the EDS were classified into three sections and ten classes. The *N* column represents the number of farms where the ES or EDS was mentioned by respondents

EDS (± 1.2 SD) during interviews. Most farmers (*N* = 39) reported both ES and EDS, with three only mentioning ES and three only mentioning EDS.

Four types of E(D)S providers were identified at different organizational levels: (i) forest areas as a whole that, among other things, limit soil erosion and provide food resources to cattle, (ii) trees and forest plants that provide more specific E(D)S such as timber, shelter to cattle, or damage to buildings if trees fall, (iii) wildlife that mainly poses raiding/predation issues on crops and livestock, but is also valued for recreation and wild game provisioning, and (iv) rivers and water courses appreciated for angling, fishing, and nature-based tourism as well as drinking sources for cattle (Fig. 2).

The most cited ES (*N* = 32) was the sheltering effect of rural forests for reared animals, including protecting cattle from sun, wind and cold. This ES motivated farmers to maintain trees in their pastures, mostly in the less productive areas: "*We maintain a patch of forest in almost all winter pastures to protect animals from wind, cold, sun,* etc. *[…]. These areas are generally stony, so pasture grass does not grow. It would be useless to remove these forest patches as we would not be able to plant anything there anyway.*" (F-Bon-30). In addition to providing shelter, forests were appreciated as habitats with feeding resources for cattle (*N* = 15), enabling diet diversification with tree fruits and leaves and different types of grass. Letting cattle graze in forests was also considered beneficial to tree seed dissemination: "*We know that ruminants and other animals eat and sow seeds […]. Here is a bocaiuva [*Acrocomia aculeata*]: there are many of them all over the farm, thanks to animals.*" (F-Bon-28).

Regarding provisioning ES, dead trees and trees cut down during pasture clearing and forest conversion were appreciated as sources of firewood (*N* = 7) and, more importantly, timber (*N* = 25) for building fences and houses. However, eight farmers explicitly stated that they tended to buy firewood rather than using their own wood due to the low price of purchased firewood and the difficulty of obtaining a permit to cut down trees. Fruit trees were also frequently cited as provisioning ES (*N* = 14), either planted tree species such as citrus (*Citrus spp.*) or wild native species such as guavira (*Campomanesia xanthocarpa*) and jatoba (*Hymenaea courbaril*).

Cultural ES were less salient in interviews, although farmers mentioned the importance of forested areas for nature-based tourism (*N* = 8), for the overall beauty of the area (*N* = 5), and for observation and walking experiences (*N* = 5). Conversely, several ES that are known to be key to agricultural activities, such as the maintenance of water sources and disease control, were rarely mentioned (Table 1).

In terms of EDS, the farmers mentioned wild animals living in forests and their predation of cattle (*N* = 30) and raiding of crops (*N* = 27). In particular, jaguars (*Panthera onca*) were reported as preying on calves and, to a lesser extent, adult zebus: "*Jaguars attack 0- to 3-month-old calves and can kill up to two calves per day [in the period when the calves are nursing]. Last year, I lost four, and already*

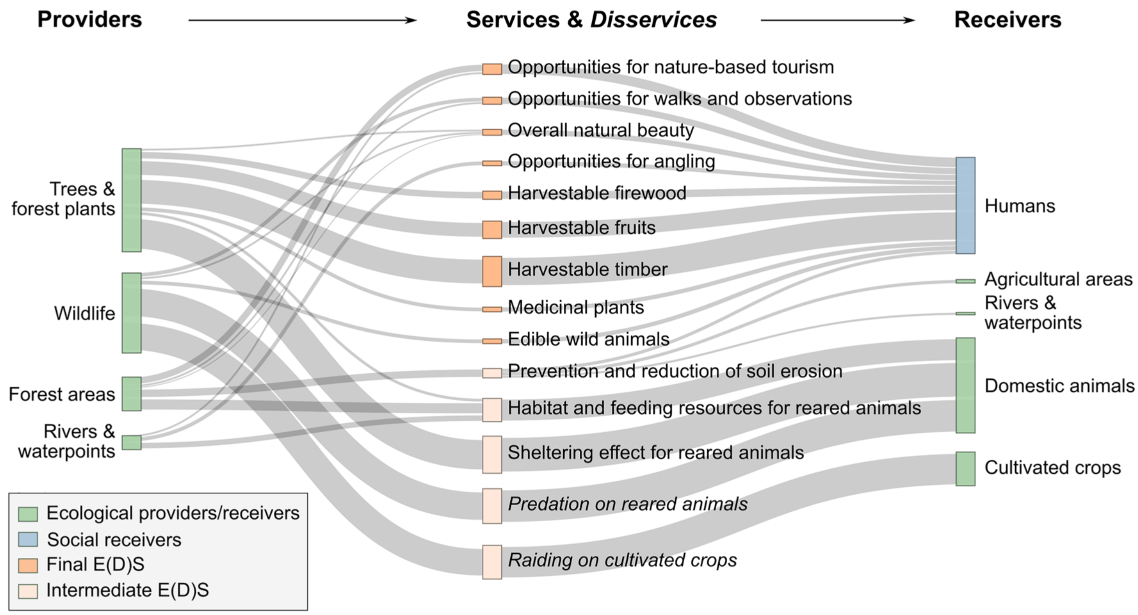

Fig. 2 Sankey diagram illustrating the main flows of services and disservices (in italics) between providers (left) and receivers (right) according to their saliency in interviews with farmers. For the sake of visibility, only the services and disservices mentioned by > 3 respondents are shown, and the feedback loops from receivers to providers are not represented

26 this year. They also attack one to two adult cows per year." (F-Bon-01). However, some farmers stated that cattle predation did not significantly impact their activities: "*As [jaguars] only attack one calf every 2 to 3 months, considering the size of the farm, it's not a big problem.*" (F-Bon-12). Crop raiding was also considered a significant EDS, in particular for maize, which is eaten by different wild pig species, including collared peccary (*Pecari tajacu*), white-lipped pecary (*Tayassu pecari*), and wild boars (*Sus scrofa*). Certain farmers stated that the resulting crop damage was significant: "*In general, over 100 hectares [of maize]—one-third of the area—is destroyed.*" (F-Bon-22). Other farmers said they were little impacted: "*Pigs are problematic, but not that much: from over 1000 hectares they might eat two.*" (F-Bon-28). These two contrasting perspectives might be partly explained by how farmers deal with EDS (see Sect. 4.3).

Farmers' perspectives on changes in E(D)S

Respondents pointed to the expansion of soy cultivation as a key driver of change in the region. According to them, this expansion involves the conversion of either pasture or forest into cultivated areas, which is regulated by Brazilian legislation, with cascading effects on E(D)S and associated detriments and benefits (Fig. 3).

The first cascading effect reported by respondents was related to converting forest into cultivated areas and pastures, leading to a decrease in natural habitats and an increase in livestock predation: "*Wild animals attack domestic animals because they have no other animals to prey on anymore. They do not have food in nature anymore because half of the animals have been killed by humans, and the other half had to leave because there are no more natural areas.*" (F-Bod-13).

According to respondents, crop expansion mainly occurs over old pastures (which are less expensive to convert than forests), putting pressure on remaining forests for the creation of new pastures, and therefore on wildlife habitats. This results in less wild prey (in particular for jaguars), making carnivores more prone to prey on farm animals (Fig. 3).

The second cascading effect was related to the expansion of cultivated areas, which caused a decline in erosion control: "*The Prata River is polluted, starting 30 km upstream from the farm, an area where the quantity of cultivated areas has increased, which causes landslides and dirty water in the river. […] This has impacted tourism because the water was dirty during the rainy season, so we couldn't practice certain activities on the farm such as diving.*" (F-Jar-03). In a region where tourism is an important economic sector and many farms offer tourist attractions and facilities, this reduced erosion control was heavily incriminated for its impact on river quality and on dependent tourist activities such as snorkeling and swimming (Fig. 3). According to respondents, there was also a vicious circle between crop expansion, increased invasive species and increased crop raiding. The main culprits are pig species, especially wild boar, which is an invasive non-native species in the region: "*The forest is a refuge for*

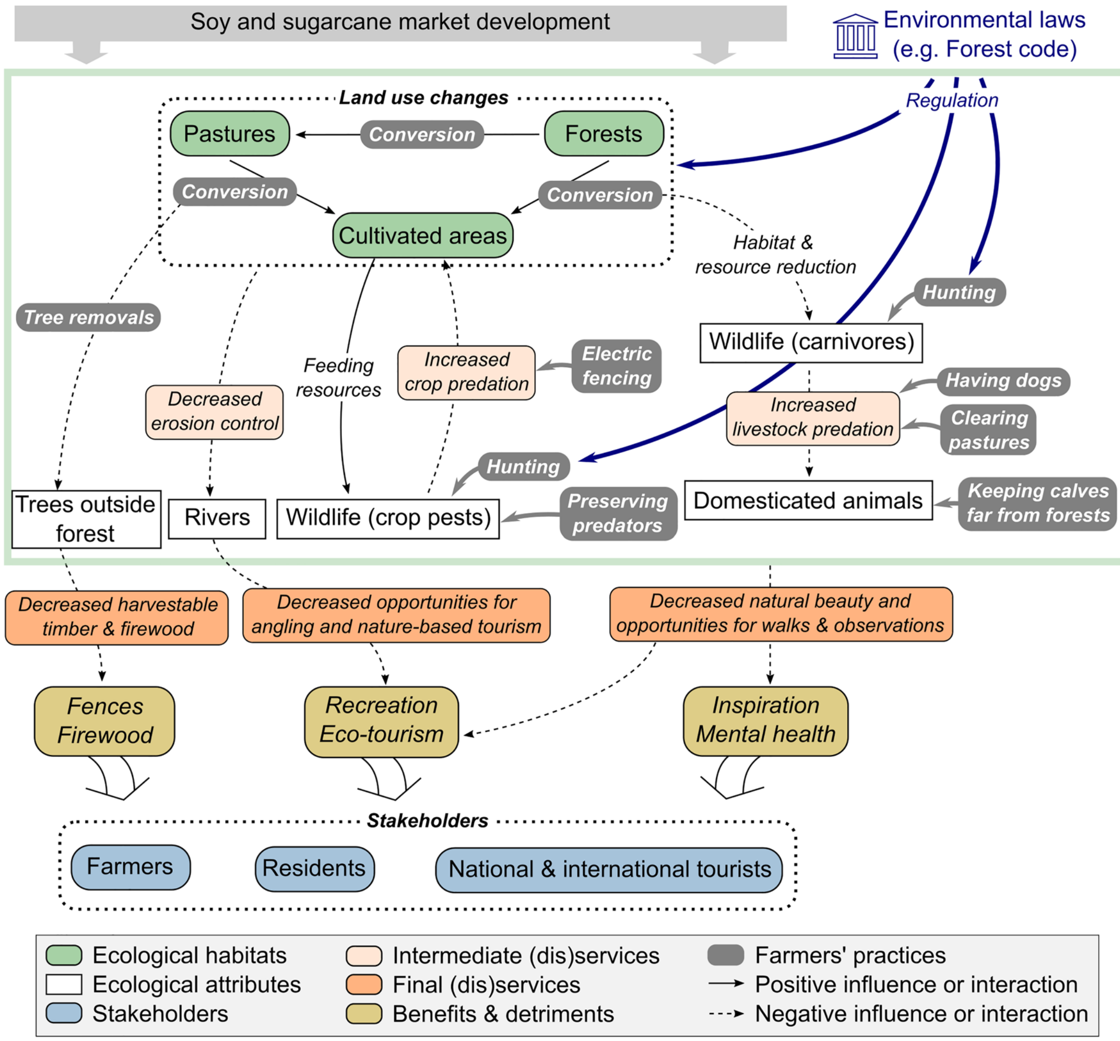

Fig. 3 Diagram summarizing the cascading effects of external factors on land use and subsequent ecological attributes and processes, key ecosystem services and disservices, and associated benefits and detriments in the case study area. This diagram reflects the perspectives of the interviewed farmers on these dynamics and focuses on the main services and disservices reported by respondents. It highlights the farmers' practices that either participate in the different dynamics or that aim at coping with main ecosystem disservices

animals and maize fields provide them food. […] They were less interested in [grazing] pastures—we hardly used to see them." (F-Bon-19). This problem was reinforced by the fact that crops are being expanded in areas where there are only a few remnants of natural habitats, and thus few wild predators: "*Do you think pigs prefer going to the mountain range over there or to eat maize here? They will come here since there is abundant food and no predators. Why are pigs a problem? Because today, we do not hunt them.*" (F-Bon-28).

Farmers' practices for coping with EDS

Farmers are actors in the ongoing changes in land use, but they also adapt their practices to the changes they perceive (Fig. 3). In our analysis, we focused on the preventive and regulating practices they use to cope with EDS and their increased incidence.

The preventive practices were principally aimed at decreasing farm vulnerability and exposure to EDS. To prevent cattle predation, farmers stated that they (i) own dogs, whose presence deters carnivores from entering farms, (ii) maintain clear, open pastures so predators have no hiding places and are more visible, and (iii) keep calves away from forests and close to houses, where predators are less prone to approach, as explained by several farmers: "*We have started to manage livestock in a different way. As jaguars were eating calves, we moved them away from forest areas and put the oldest cows close to forests.*" (F-Bon-29). Farmers also rethought the location of crops: "*The first two years we cultivated crops here, half of the maize was eaten by pigs because* *we didn't pay attention. Now we avoid cultivating close to forests.*" (F-Bon-30). In addition, electric fencing was advocated by some to protect crops from predators, although several farmers were not convinced by its effectiveness: *"[Wild animals] enter the fenced fields, then they can't get out and are left stuck inside.*" (F-Bon-29). Overall, our qualitative analysis suggested that the feasibility and reliability of preventive practices were partly influenced by the location of the farm, such as the proportion of areas far from forests and the local predation pressure, explaining the different points of view highlighted in Sect. 4.1.

In addition to preventive practices that concerned farm management choices, farmers stated that they implement regulating practices that aim to mitigate EDS by acting on their ecological providers. For example, many cited the necessity to hunt pigs (peccaries and wild boars) and jaguars to regulate their populations and reduce crop raiding and livestock predation. However, environmental laws ban hunting native species, except for self-defense, and only allow hunting invasive species such as wild boar. While the majority of respondents said they comply with these laws, some indicated that they do hunt: "*The easiest way [to hunt jaguars] is when they kill calves. They take and hide the carcass, which can be tracked, and they return to eat it when they get hungry. So it's possible to ambush them.*" (F-Bon-01). However, two farmers involved in crop production stated they wish to increase the population of natural predators to control certain EDS providers: "*Jaguars prevent peccaries from entering the fields, but there are not enough of them to prevent damage from peccaries. It would be necessary to breed jaguars to no longer have peccaries on the farms.*" (F-Bon-10).

Discussion

Potential and limitations of the E(D)S cascade model

After more than a decade of debates around the EDS concept, the idea of taking into account the negative impacts of ecosystems on human well-being as well as their positive contributions has gained momentum in sustainability research (Díaz et al. 2018; Blanco et al. 2019a). The E(D)S cascade model we developed seems to provide a robust and operational, yet flexible, model to allow this joint assessment.

In our case study, the model proved useful to shed light on the diverse synergies and trade-offs that occur between ES and EDS and, importantly, on the distinction between intermediate and final ecosystem disservices. While Shackleton et al. (2016) highlighted the difference between direct and indirect EDS, the authors did not discuss its symmetry with intermediate and final ES nor its analytical implication: from the standpoint of environmental accounting, where double counting must be avoided, only final E(D)S should be considered (see also Fisher et al. 2009). This is because the influence of intermediate EDS—i.e. the diminution of an ES or the reinforcement of another EDS—would already be accounted for by final E(D)S. For example, the tangible cost of livestock predation is already taken into account when valuing the benefits derived from meat production. However, livestock predation should sometimes be considered as a final EDS for its psychological consequences (Methorst et al. 2020). Thus, just as with ES (Fisher et al. 2009), the context and objectives of the analyst determine whether a given EDS is final or intermediate. Of course, this distinction between intermediate and final E(D)S might not always be critical to all biophysical and socio-cultural valuation studies. For example, in our case study, the role of rural forests in controlling erosion was appreciated by farmers as it allowed maintaining fertile agricultural land, clean rivers for snorkeling activities, and, more generally, limited gullies and riverbank alteration. Thus, in these farmers' eyes, erosion control is both an intermediate and a final ES depending on the benefit considered. In this case, the analysis of farmers' perspectives does not absolutely require that the analyst make the distinction between an intermediate or final E(D)S.

The model also helped to clarify (i) what constitutes an EDS and (ii) the delineation between ecological phenomena, EDS, and associated detriments or costs. In the existing literature, there is persisting ambiguity on these two aspects. For example, fear of crime in urban green spaces is sometimes considered as an EDS (e.g. Pinto et al. 2021). Yet this is not an ecological phenomenon, so it does not fall into the scope of the EDS definition proposed in our model (see Sect. 2.1). While social phenomena can influence the quality of people's experience with nature, we argue that it is not useful to conflate this with EDS and that another terminology or concept should be used to designate these social impacts. Furthermore, even in recent literature, the term EDS is used to designate negative ecological phenomena and costs indistinctively. For example, in Zhen et al. (2021), soil acidification and morbidity of people caused by different types of agricultural systems are both considered as EDS. However, the latter is neither a phenomenon arising from the ecosystem, nor is it caused by an ecological phenomenon, since it is linked to the use of pesticides. As suggested by previous authors (Shackleton et al. 2016), such phenomena that result from human (mis)management of ecosystems should not be considered as EDS, nor accounted as costs emanating from ecosystems.

The stricter definitions chosen for our model aim to encourage researchers and practitioners to pay greater attention to how they use the EDS concept for the sake of its overall credibility and consistency. However, we acknowledge that delineating EDS from associated costs and detriments, or delineating EDS from certain social-based phenomena, may not always be obvious or straightforward, as is the case for ES (Potschin-Young et al. 2018). Nonetheless, it seems vital to avoid E(D)S concepts becoming *panchrestons,* i.e. terms that mean so many things to different people that they are conceptually and empirically useless (Simberloff 2014). We, therefore, argue that researchers should be more rigorous and explicit about their choices in how they delimit E(D)S from other phenomena, which will help in conducting comparative analyses of different case studies and in scaling up local findings.

In terms of limitations of our E(D)S cascade model, the first is that it is not spatially explicit and does not fully unpack the social and institutional arrangements that mediate E(D)S delivery, such as multiple stakeholder interactions and formal and informal rules and norms. This limitation could be overcome by combining the model with existing E(D)S frameworks that aim to deal with these aspects (Summers et al. 2012; Barnaud et al. 2018; Vialatte et al. 2019). Second, the model is not intended to be used as an objective, dichotomous delineation of the relationship between people and ecosystems. Its goal is to orient the analysis of people's subjective opinions about their environment in order to provide more balanced and inclusive assessments of nature's positive and negative impacts. The aim of the model is to help reveal consensual and non-consensual views about ecosystems, a necessary starting point to identify potential tensions and conflicts and ultimately shared solutions toward sustainability (Buijs et al. 2011). To avoid dichotomy, it is critical to distinguish between E(D)S providers and E(D)S themselves, which allows identifying nuances in what humans consider as 'good' or 'bad'. As illustrated by our case study, many ecological phenomena simultaneously produce multiple ES and EDS, and the farmers we interviewed were perfectly aware of this duality. Destroying an ecosystem to remove an EDS might result in the loss of beneficial ES, while conversely, focusing on a given ES might lead to unanticipated EDS and costs (Friess 2016; Stokely and Betts 2020). The model is designed to help identify and navigate such complex trade-offs and synergies.

Finally, the E(D)S cascade model offers a conceptual foundation that could be the basis for designing a broadly relevant EDS typology as already exists for ES. This could also be relevant beyond the strict field of ES research, in particular in the nature's contributions to people (NCP) framework. This recent approach emphasizes the necessity of accounting for both positive and negative impacts of nature (Díaz et al. 2018). Yet it also tends to put negative impacts 'behind the scenes' in its 18 identified NCP categories: detrimental aspects of nature are included within positive contributions, such as NCP category #10, which includes the regulation of detrimental organisms. In order to reach the equal consideration of both positive and negative impacts of nature as some authors advocate (Schaubroeck 2017), putting them on the same analytical level is critical, which is the aim of this E(D)S cascade model.

Farmers' perceptions of rural forests: unpacking a complex context-specific relationship

In our qualitative socio-cultural valuation study in a region of the Mato Grosso do Sul state in Brazil, the model helped to identify farmers' systemic and dynamic visions of the benefits and detriments they associate with rural forests. To our knowledge, this topic has not been covered by previous research in this region; this is why we chose a qualitative approach and open-ended interview techniques. These were ideal to provide a preliminary understanding of the topic and its delimitation, but were not suited to detailed quantitative analyses. So, while the case study did not provide definitive results, the findings could be helpful to future research and more systematic and quantitative approaches that would allow some of our preliminary results to be confirmed or refuted. In particular, two key aspects could be further explored: (i) the extent to which individual farmers' perceptions of E(D)S are mediated by either farming practices and/or personal factors, and (ii) the relationship between farmers' perceptions and the local socio-political context.

With this proviso in mind, we found that most farmers acknowledged the duality of the impacts of rural forests, as individuals reported both ES and EDS. A few farmers mentioned only ES or only EDS, but this was mainly due to the limitations of the loose interviewing method we chose. As interviewers oriented the discussions based on the topics that inductively appeared, all interviews could not systematically cover all possible topics, in particular because of farmers' time constraints. Despite this methodological limitation, we found that farmers tended to report a larger number of ES than EDS, which is consistent with similar studies in other contexts (Ango et al. 2014; Blanco et al. 2020b). Brazilian farmers especially emphasized regulating ES and indirect EDS that impacted their crops and livestock, confirming their expertise and focus on their main source of income, but also their subjectivity. Interestingly, a larger number of intermediate E(D)S than final E(D)S were mentioned by farmers, which was even more salient for EDS than ES (Table 1). This result suggests that the negative effect of rural forests on farmer well-being is mostly indirect (i.e. through agricultural activities) rather than direct. Along with the higher number of ES mentioned than EDS, the findings also suggest that the overall (or 'net') contribution of rural forests to these farmers is positive, which is a promising lever to foster better coexistence between agriculture and biodiversity in the region.

Yet our results also tend to corroborate the hypothesis that, for a similar intensity, EDS might have a greater influence on farmers' perceptions, attitudes and behaviors than ES (also observed in Kansky and Knight 2014; Blanco et al. 2019a). When asked about rural forests, farmers were more prone to discuss negative aspects, although overall they cited less EDS than ES (in number). In addition, the frequent mention of livestock predation contrasts with the low abundance of large predators found by ecological surveys in the region (Cáceres et al. 2007). Livestock predation issues seemed to be overstated considering the negligeable share of herds effectively lost.

Two complementary hypotheses, one cognitivist and one political, may explain this imbalance between farmers' discourse and biophysical phenomena. First, neuroscientific research has shown that humans tend to have a stronger reaction to negative vs. positive stimuli, known as the 'negativity bias' (Norris 2019). In our case, this cognitive bias could explain why farmers gave disproportionate attention to certain EDS compared to their actual manifestation. It is valuable to highlight the existence of such negativity bias, as this could further challenge biodiversity conservation efforts (Buijs and Jacobs 2021). Indeed, while it is often argued that ES could help counteract certain EDS in order to foster more sustainable human–nature relationships (Teixeira et al. 2020), negativity bias might mean that higher levels of ES are necessary to compensate for a given level of EDS. While further quantitative research is required to confirm whether negativity bias affects how people perceive and react to ecosystem-based stimuli, this could open new transformational avenues: if verified, this hypothesis implies that decreasing actual and perceived EDS could be a powerful driver in creating more sustainable human–nature relationships—even more powerful than increasing actual and perceived ES.

In addition to this cognitivist hypothesis, the local socio-political context around rural forest conservation in Brazil might be a key factor in farmers' focus on EDS. The Brazilian Forest Code requires farmers in the study region to maintain native vegetation in Areas of Permanent Protection and in Legal Reserves. Furthermore, the creation of the Serra da Bodoquena National Park in 2000, partly on private land, has been a source of tension between farmers and environmental agencies. In this context, farmers tended to have a negative attitude toward forest conservation policies that substantially impact the proportion of land they can use for agriculture: "*Brazilian farmers suffer from environmental issues […]. Over the 100 hectares I was talking about, 80 hectares remain after you remove Legal Reserves, and then you remove some land where there are rivers, so 70 hectares remain, and if you have hills, then you eventually can only use 50 hectares.*" (F-Bon-28). The latent conflict between farmers and environmentalists in the region might influence the former's attitudes toward forests and biodiversity, and the attention they pay to associated E(D)S, as has been shown in other contexts with human–wildlife conflicts (Hodgson et al. 2020). One study has found that when people are affected by EDS, they tend to have less positive attitudes toward biodiversity conservation (Nyhus et al. 2000). This suggests that focusing on EDS and finding ways to reduce these could help improve local support for conservation initiatives. In our case study, these two cognitivist and socio-political hypotheses call for further research to better understand the many factors that influence farmers' relationships with rural forests, which might include the following: (i) the farming systems (which are more or less vulnerable to different EDS), (ii) farmers' personal views and history (which might influence farmers' tolerance to EDS) and (iii) farmers' relationships with local stakeholders (which might influence farmers' socio-political discourse and opinions).

Finally, we found that some E(D)S were absent from farmers' discourse. This was the case for certain regulating ES such as the maintenance of water sources and disease control, which were perhaps too indirectly connected to rural forests in farmers' eyes to be mentioned. This was also the case for cultural EDS, which were totally absent (Table 1). This result may be explained by the ambiguity around this EDS category, which has also been highlighted for cultural ES. Beyond the argument that the 'cultural ES' category tends to isolate cultural aspects that transcend all ES categories—many cultural benefits being associated with provisioning and regulating ES (Chan et al. 2012)—it has also been argued that cultural ES should be understood as benefits rather than services (Fisher et al. 2009). For example, enjoying a walk in the forest is a benefit (not an ecological phenomenon that provides a service). The provider of this benefit is the forest, at least as long as there are walking trails in it. According to the CICES, the ES associated with this benefit is the "opportunity for walks" that the forest offers (Haines-Young and Potschin 2018). Yet this example shows that differentiating the ES provider from the ES, and the ES from the benefit, is particularly tricky for cultural ES. Similarly, in our study, farmers raised the fear of being attacked by predators, which we considered as a detriment rather than a cultural EDS. The EDS associated with this detriment would be the chance of being attacked, but this EDS was already accounted for in the EDS 'Animal attacks on people' (D3.1, Table 1). Thus, in this case the E(D)S cascade model identifies only one EDS—i.e. animal attacks on people—producing two types of detriments: physical injuries and a feeling of insecurity. This not only explains the absence of cultural EDS in our study, but also highlights the need to elaborate a consistent EDS typology as a next step to further operationalize the E(D)S cascade model.

Taking into account ecosystem disservices: an alternative pathway toward sustainability

The information identified through the use of our model in the case study shows promise in helping to address sustainability issues. The model allowed us to demonstrate that in farmers' eyes, rural forests are a major source of ES and that EDS are more marginal (at least in number). This result offers a potential avenue to go beyond the traditional conflict between productive agriculture and biodiversity conservation, and to move forward together on reconciling these two key socio-environmental challenges.

The analysis also identified a vicious circle between crop expansion, soil erosion and invasive species that could have major economic and ecological consequences in the future. The conversion of pastures to cultivate maize and soy was reported as altering soil erosion control and river quality for snorkeling, while contributing to the proliferation of wild boar. Yet, whereas Brazilian environmental law is very strict regarding deforestation, pasture conversion into cropland is less restricted, and the farmers we interviewed did not mention having any difficulty obtaining the required permit (contrary to obtaining authorization for clearing forest patches). In this sense, the application of the E(D)S cascade model allowed us to point to a legislative blind spot and to raise the alarm about the very concrete consequences that crop expansion could have in the region, namely the decrease of the area's tourism value, the proliferation of certain invasive species, and the potential exacerbation of human–wildlife conflicts.

The findings also showed that the capacity of ecosystems to provide E(D)S is closely linked with agricultural management practices (Stokely and Betts 2020). In particular, our results highlighted that farmers use different preventive and regulating practices to mitigate EDS that do not necessarily interfere with ecological providers (Ango et al. 2014). For example, changing the location of crop fields or areas for raising calves within farms allowed crop raiding and livestock predation to be reduced without impacting peccaries and jaguars. Highlighting such adaptive practices, and better supporting them through ad-hoc incentives (Marchini et al. 2011), could be a promising strategy to improve the local coexistence of agriculture and biodiversity.

In a more global perspective, reinforcing research on EDS could lead to a major shift in sustainability research and policy paradigms. The ES concept was essentially introduced to raise the awareness of people and policymakers on the many benefits provided by ecosystems. The main idea was to convince human societies that biodiversity conservation was a sound strategy, even on a purely economic basis. To complement this idea, the EDS concept acknowledges that biodiversity conservation can also generate costs for certain people, which is critical to consider and evaluate to avoid environmental inequalities (McElwee 2010). This concept also allows a better understanding of the factors that undermine biodiversity conservation, and the reasons why people are sometimes skeptical about it and might act against it. As the case study demonstrated, this focus can help find alternative solutions that promote sustainability, such as those implemented by the farmers who adapted their practices to reduce their vulnerability to EDS without necessarily killing the animals that caused crop or livestock losses. Giving more consideration to EDS would allow a twofold strategy for biodiversity conservation: (i) reinforcing ES and associated benefits, in the hope that this contributes to preserving ecosystems, and (ii) reducing EDS and associated costs, helping people to become less vulnerable to EDS in a sustainable manner. Ultimately, policymakers would play a key role in supporting the adoption of preventive practices that aim to decrease people's vulnerability and exposure to EDS, while fighting against practices that participate in ecosystem degradation. This would represent a significant change in current sustainability paradigms.

Conclusion

Providing more inclusive and balanced assessments of the multiple impacts of ecosystems on human societies is a major challenge in sustainability science. The novel cascade model devised in this study integrates both ES and EDS so both can be jointly assessed. This was tested in a case study to explore Brazilian farmers' relationships with rural forests in a region in Mato Grosso do Sul. The model proved valuable in showing that these farmers associate a broad spectrum of ES and EDS with rural forests, revealing their perspectives about how rural forests interact, positively and negatively, with their farms. The results highlighted that just like ES, ecosystem disservices are coproduced by ecosystems and people. They also revealed ways how the EDS perceived as most problematic can be mitigated by adapting human practices, in particular farming systems, without impacting biodiversity. Ultimately, this novel E(D)S cascade model offers a conceptual basis to better understand social-ecological systems and better foster the integration of EDS in ES research, helping to open new avenues toward more effective sustainability policy.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-021-01049-z.

Acknowledgements This research was funded by the Brazilian National Council for Scientific and Technological Development (CNPq) (in particular through grants to FLS: Process 301306/2018-4, and to FOR), and by the Regional Council of the Pays de la Loire (France) through the CASEST (Anthropogenic Constraints to Tropical Savanna Socio-Ecological Systems) project. BB received a Rhodes University Postgraduate Scholarship (number: 2000108). We also received financial support from the Wetlands International office in Campo Grande and the MUPAN (Women in Action in the Pantanal) association. We would also like to thank all those from the farms we visited who accepted to be interviewed, as well as Sandro Roberto da Silva Pereira from the Chico Mendes Institute for Biodiversity Conservation (ICMBio) and Nino Rodrigo from the Brazilian Agency for

Agricultural and Rural Development (AGRAER) for their valuable help in the field. Finally, we are grateful to all those who participated in the interviews with farmers, as translators or assistants, including Aurélie de Palmas, Inès Fillon, Fabio Bolzan, Guilherme Dalponti, Aline Giroux, and Dinah Madruga.

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