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Using the available indicators of potential biodiversity damage for Life Cycle Assessment on soybean crop according to Brazilian ecoregions

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A R T I C L E I N F O

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Characterization factors
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A B S T R A C T

The purpose of the study was to evaluate the use of and suggest possible adjustments to indicators of biodiversity loss for LCA proposed by Chaudhary and Books (2018). For this, we analyzed soybean production in Brazil. Potential damage to biodiversity has been determined for all Brazilian ecoregions: the Amazon; the Atlantic forest; Caatinga; Cerrado; Pampas; and the Pantanal. Two dimensions of assessment were considered – global and regional – in addition to Average-country. An adjustment was proposed for the vulnerability coefficient to the indicators Average-country Brazil: the Regional Species Fragility Index (FI). Two inventories were created using two different functional units: area of production of soybean by ecoregion (year m^2); and area corresponding to production of 1 kg of soybean (year m^2). Thus, we observed that when the indicators of aggregate values were adopted, the Atlantic Forest was the ecoregion most affected by the crop. Regarding the assessments of the Potential Biodiversity Damage (BD) Global and Regional indicators, the Atlantic Forest and the Amazon were the ecoregions that suffered the highest impacts, mainly on plants, birds and amphibians taxa. Besides, the impacts at the global level were always more expressive than the regional ones. Due to this, we noticed that the results were influenced by the Vulnerability Score (VS). The suitability of the VS for FI is relevant and the adjustment in the equation can be suggested for other regions. Considering the results found here, to prevent regional impacts, technical measures such as extensive farming and crop rotation should be prioritized as impact mitigation actions. However, political measures tend to be more effective at geographic levels when addressing more than one ecoregion, due to the standardization of preservation procedures. Thus, from the results reported here, we conclude that the FI is relevant to diagnose measures at the administrative geographic levels of the ecoregions present in a single country, and the applied indicators reinforce that the Atlantic Forest ecoregion is the most vulnerable due to the replacement of wild forest for cultivated areas, which includes soybean crops.

1. Introduction

In Brazil, the agricultural sector contributed 21.4% to the gross domestic product (GDP) and 43% of the country's exports in 2019 (CNA, 2020). Soybean is the most important commodity of Brazilian agriculture, and soybean farming has intensified in the last decades (Hirakuri and Lazzaroto, 2014). From 1997 to 2016, yields increased 3.5 million tons (13.4%); areas increased 1.05 million hectare (9.2%); and production increased in 32.7 kg ha^{-1} (1.42%) (Balbinot et al., 2017). Thus, Brazil occupies a prominent position in the global supply and demand of products of the soybean agro-industrial complex.

Agriculture intensification demands agricultural inputs and sometimes agricultural practices that may lead to the destruction of ecosystems and depredation of natural resources. Environmental issues are considered to be of relatively low priority to the productive sector. However, concern about environment destruction has been growing around the world, and discussions on sustainability are presently on the agenda. Changes in land use is one of the main topics in the scientific field due to their impacts, such as degradation of ecoregions, depletion of natural resources and biodiversity loss (Foley et al., 2005).

The Brazilian territory comprises six biomes that are biodiversity hotspots. These ecoregions have suffered high degradation due to land

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use changes. The Atlantic Forest – Brazil's third largest biome and the second largest tropical rainforest in the American continent – has historically been the most violated. As a result of settlements and agricultural practices, presently it is one of the most devastated ecoregions in the planet (Martins, 2011). Thus, the development of initiatives to recover part of these natural areas and to preserve remaining fragments is urgent. Assessment of the current conditions and the possible effects of these problems are fundamental. Choosing the suitable methodology to assess damage and potential effects is priority.

Life Cycle Assessment (LCA) is considered one of the most promising methodologies for environmental assessments. LCA is a scientific tool to assess different types of environmental impacts of products or processes (Hellweg and Milà i Canals, 2014). In addition, the impacts may be categorized and related to the production stages. The same applies to changes in land use; LCA allows to identify them through the different stages of production (Milà i Canals, 2007). There has been a lot of effort to expand LCA's range of impacts, such as assessing biodiversity loss, ecological functions and ecosystem services. Efforts have been made to reach a consensus on how to conduct these assessments, because different methods may lead to different results (UNEP, FAO, JRC). Biodiversity loss caused by land use is one of the most important categories in this field, and it has received particular attention. The assessment of biodiversity loss is very complex and geographically specific, which makes it difficult to integrate it into LCA. Thus, the UNEP/SETAC Life Cycle Initiative developed a guide which includes the past efforts and new challenges faced when modelling these impacts.

The guide recommends the use of a set of indicators and Characterization Factors (CF), which can generate assessments in two geographical levels: administrative (country); "natural" (ecoregion); and Average-country (Chaudhary et al., 2015). Differentiation between global and regional is given by the inclusion of a coefficient of species vulnerability, the Vulnerability Score (VS), determined for each ecoregion. The VS, which represents the change in relation to the abundance of species within an ecoregion, is applied to differentiate the geographical levels of the assessments between global and regional damage.

Chaudhary and Books (2018) have updated the CFs since Chaudhary et al. (2015), modifying part of their values between publications. Furthermore, in their most recent publication, they have included VS for plant taxon, which was previously absent. However, this publication does not present a regional Average-country, only global. as Although it could be interesting to use regional-country values for the application of policies, this study proposed the creation of a Regional Species Fragility Index (FI), with the purpose of enabling the use of Average-country indicators to assess regional dimensions in Brazil. This implies the use of these indicators in faster assessments, maintaining their qualities, in order to contribute to their dissemination for diagnostics at administrative geographical levels, as well as to determine action measures for the impacts, considering their ecoregions directly and solely, at their natural geographical levels.

Hence, the purpose of this study was to assess the applicability of and eventually suggest adjustments to indicators to assess biodiversity loss according to changes in land use in a LCA study. A case study assessed the replacement of wild vegetation for soybean crops in Brazil under different ecoregions. In addition, from the results obtained, possible measures to mitigate these impacts were discussed.

2. Materials and methods

2.1. Production of soybean in Brazilian ecoregions

Indicators of potential damage to biodiversity – biodiversity loss – were applied to Brazilian ecoregions in which soybean is cultivated. Following Chaudhary et al. (2015) and Chaudhary and Books (2018), the World Wildlife Fund (WWF) codes (Table 1) were used to identify and classify the ecoregions.

Table 1
Ecoregion codes and size of the total areas (year m^2) of soybean for each ecoregion in Brazil and for Average-country Brazil.

Ecoregions	Ecoregion codes[1]	Production of soybean (kg/m^2)[2]	Size of the area total (m^2)[2]
Amazon	NT0168	3.28E−01	5.34E+10
Atlantic Forest	NT0150	3.49E−01	1.29E+11
Caatinga	NT1304	3.28E−01	1.73E+09
Cerrado	NT0704	3.53E−01	1.79E+11
Pampas	NT0710	2.67E−01	2.95E+10
Pantanal	NT0907	3.52E−01	1.78E+09
Average-country Brazil	–	3.30E−01	3.93E+11

Source: [1]WWF (2019); [2]Ibge (2019).

Fig. 1 shows the areas where there is soybean farming in each ecoregion (ArcGIS, v.10.5). The information to define the farming zones were obtained from the PAM (Municipal Agricultural Production) database [Ibge (Instituto Brasileiro De Geografia E Estatística – Ibge) 2018 annual survey (Ibge, 2019)]. Thereby, the values of production of soybean found for each ecoregion are presented in Table 1.

2.2. Indicators of potential biodiversity damage (BD)

To assess the impacts of potential damage to biodiversity caused by soybean farming in Brazil, the indicators proposed by Chaudhary et al. (2015) were initially consulted. These indicators were preliminarily recommended by the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), through the Global Guidance for Life Cycle Impact Assessment Impact Indicator (UNEP, 2016).

This study applied the indicators of Potential Biodiversity Damage (BD), which were updated to a new version in Chaudhary and Books (2018), in which new values of Characterization Factors (CFs) were included. The CFs, according to Chaudhary and Books (2018), represent the results of damage for potential loss of species per square meter (m^2) of crop for the taxa: mammals, birds, amphibians, reptiles and plants. The damage for the five different types of land use (managed forests, plantations, pasture, cropland, urban), in three levels of intensity (minimal, light and intense), for each one of the 804 terrestrial ecoregions, were then accessed. The CFs, in addition to assessing by taxa, can assess by aggregate values (regional and global).

The CFs were developed by combining the Countryside SAR model (Pereira et al., 2014), including, in the case of global biodiversity damage, Vulnerability Scores (VS), which are based on the threat level attributed to species. The VS was developed by the International Union for Conservation of Nature (IUCN) (Chaudhary and Books, 2018; Chaudhary and Brooks, 2019).

Thus, the impact of biodiversity potential damage for regional assessments ($BD_{Regional}$) was determined by Equation (1):

$$BD_{Regional,g} = (CF_{regional,g,i,j})^{*}A_{i,j} \quad (1)$$

where g = taxonomic group (taxa); i = land use; j = ecoregion; $A_{i,j}$ (m^2) = total crop area . The $BD_{Global,g}$ is indicated in Potentially Disappeared Fraction (PDF) * year m^2.

$$BD_{Global,g} = CF_{regionalal,g,i,j}{}^{*}Vs^{*}A_{i,j} \quad (2)$$

where g = taxonomic group (taxa); i = land use; j = ecoregion; VS = vulnerability score; $A_{i,j}$ (m^2) = total crop area. The $BD_{Global,g}$ is indicated in Potentially Disappeared Fraction (PDF) * year m^2.

2.3. Characterization Factors (CFs)

All Brazilian ecoregions where soybean is grown were taken into account, in addition to Average-country Brazil CF for the five taxa and

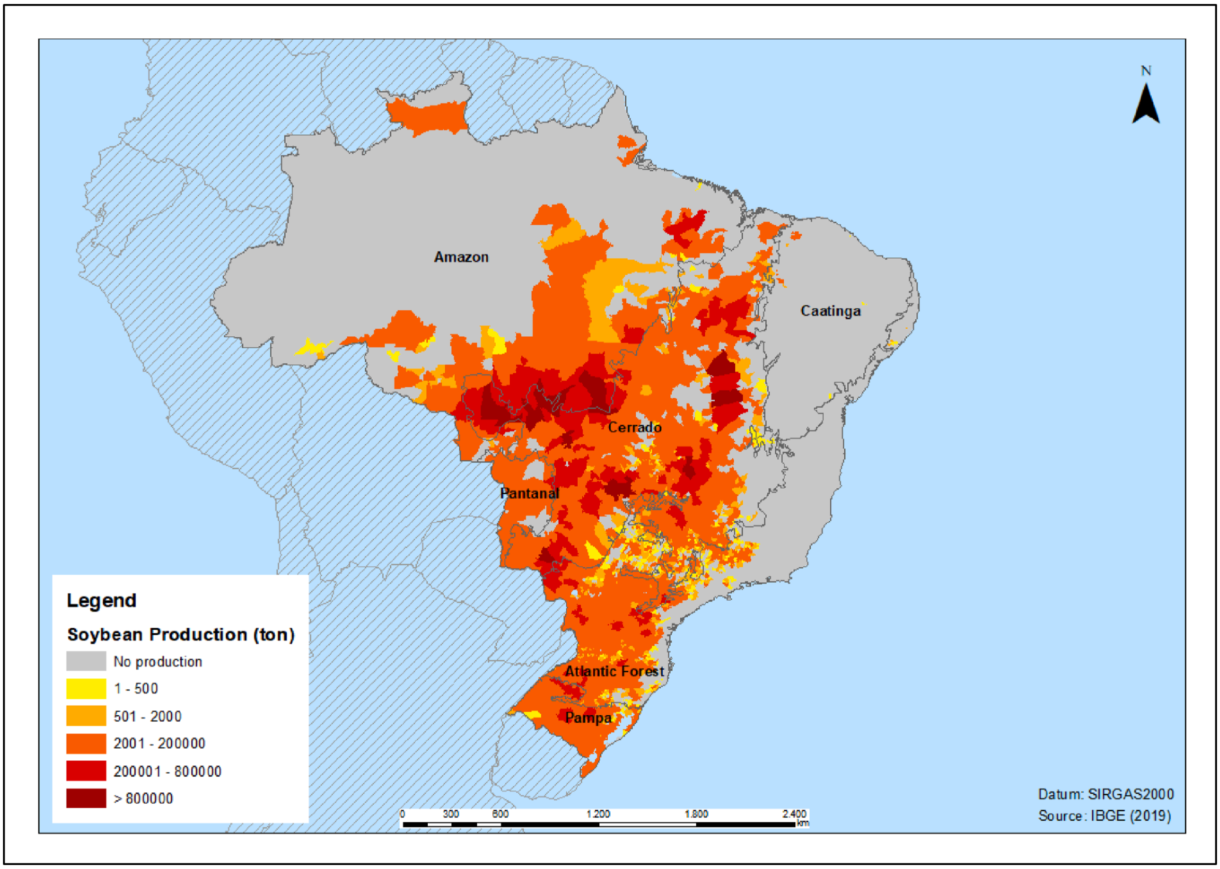

Fig. 1. Areas where there is soybean farming in each ecoregion where soybean is grown in Brazil. Source: Ibge (2019).

aggregated values. The CFs for Intense Cropland Use were adopted (confidence interval = 95%).

The "Intensive Use" level was adopted due to the fact that production of soybean in Brazil, according to Balbinot et al. (2017), Dias et al. (2018), and Franchini et al. (2011), includes most of the features necessary to achieve this level of intensity: large-scale production, soil preparation, application of inorganic fertilizers, application of pesticides, irrigation, mechanization, and no crop rotation (Chaudhary and Books, 2018).

The no-tillage production system, in general, is practiced for soybean cultivation in Brazilian croplands. However, this practice is not included in any level of intensity of the adopted indicators, neither are the indicators capable of differentiating practices such as tillage or no-tillage. Therefore, it was disregarded.

The CF_{Global} values are shown in Table 2 and include, besides the ecoregions individually, an average for the country. Table 3 shows the $CF_{Regional}$ values.

2.4. Vulnerability score (VS) for Average-country Brazil

The CFs for Average-country Brazil, according to Chaudhary and Books (2018), and updated since Chaudhary et al. (2015), proposed changes in part of their values. Furthermore, in their most recent publication, VS for plant taxon have been included. However, Chaudhary and Books (2018) do not propose a regional Average-country, just the global one.

In order to test the degree of biodiversity damage at country level, we propose the Regional Species Fragility Index (FI). The FI was calculated by adapting the Vulnerability Score (VS). The VS_{Global} is determined by using Equation (3) (Chaudhary et al., 2015; Chaudhary and Books, 2018). The total values of species ($S_{tot,g}$) were established previously by Chaudhary et al. (2015), as follows: 5386, 10104, 3384, 6251, and 321,212 for mammals, birds, reptiles, amphibians and plants, respectively.

Table 2
Global Characterization Factor (CF_{Global}) values per ecoregions and Average-country Brazil for each taxon and aggregated values, expressed as potential loss of species * year m^2, in cropland intense use.

Biomes	Ecoregions code[1]	Taxonomic groups					
		Mamals	Birds	Amphibians	Reptiles	Plants	Aggregated
		CF^2_{Global}					
Amazon	NT0168	7.23E−12	1.40E−11	6.08E−12	3.68E−13	5.23E−11	1.75E−13
Atlantic Forest	NT0150	1.64E−11	2.75E−11	3.24E−11	1.13E-12	4.15E−11	3.88E−13
Caatinga	NT1304	4.58E−12	7.21E−12	6.01E−12	1.01E−12	3.72E−12	1.01E−13
Cerrado	NT0704	5.25E−12	7.31E−12	7.97E−12	1.09E−12	7.51E−12	1.10E−13
Pampas	NT0710	8.74E−12	9.25E−12	8.83E−12	9.76E−13	1.66E−11	1.48E−13
Pantanal	NT0907	4.42E−12	6.91E−12	5.05E−12	7.59E−13	1.39E−11	9.58E−14
Average-country CF Brazil	–	1.00E−11	1.54E−11	2.20E−11	1.14E−12	1.19E−10	2.44E−13

Source: [1]WWF (2019); [2]Chaudhary and Books (2018).

Table 3
Regional Characterization Factor ($CF_{Regional}$) values for ecoregions and Average-country Brazil for each taxon and aggregated values, expressed as potential loss of species * year m^2, in cropland intense use.

Biomes	Ecoregions code[1]	Taxonomic groups					
		Mamals	Birds	Amphibians	Reptiles	Plants	Aggregated
		$CF^2_{Regional}$					
Amazon	NT0168	2.58E−10	8.08E−10	8.21E−11	8.96E−11	4.33E−09	1.61E−14
Atlantic Forest	NT0150	2.81E−10	7.67E−10	3.94E−10	1.04E−10	4.70E−09	1.80E−14
Caatinga	NT1304	6.45E−11	1.30E−10	2.08E−11	2.97E−11	4.95E−10	2.14E−15
Cerrado	NT0704	4.36E−11	9.79E−11	3.52E−11	2.78E−11	8.79E−10	3.13E−15
Pampas	NT0710	1.24E−10	4.30E−10	1.45E−10	7.20E−11	2.18E−09	8.53E−15
Pantanal	NT0907	3.18E−10	7.82E−10	9.87E−11	1.39E−10	2.51E−09	1.11E−14
Average-country CF Brazil	–	1.35E−09	1.76E−09	7.44E−10	1.85E−10	3.04E−08	2.62E−14

Source: [1]WWF (2019); [2]Chaudhary and Books (2018).

$$VS_{g,Global} = \frac{\sum_{j=1}^{804} VS_{g,j} * S_{org,g,j}}{S_{tot,g}} \quad (3)$$

where g = taxonomic groups (taxa); j = ecoregion; $S_{org,g,j}$ = species richness; $S_{tot,g}$ = total species for each taxa.

The VS_{Global} and the IF_{Brazil} values are shown in Table 4. Only the six ecoregions within the Brazilian territory were taken in account instead of the 804 classified in the world (Chaudhary et al., 2015; Chaudhary and Books, 2018) to adapt Equation (3) for the Regional Species Fragility Index (FI), Brazil, into Equation (4).

$$FI_{g,Brazil} = \frac{\sum_{j=1}^{6} VS_{g,j} * S_{org,g,j}}{S_{tot,g}} \quad (4)$$

where g = taxonomic groups (taxa); j = ecoregion; $S_{org,g,j}$ = species richness; $S_{tot,g}$ = total species for each taxa.

2.5. Life cycle inventory

Two inventories were created to estimate the impacts of BD. The first one, in which the size of the cropland areas for production of 1 kg of soybean was adopted as the functional unit, and another in which the size of areas cultivated by ecoregion was considered as the functional unit (Fig. 2).

3. Results

Results are separated in two sections. The first one presents the results of the Aggregated values, Global and Regional, separately. Next, the results of the taxonomic groups (taxa) are presented for the Global and Regional values, together.

3.1. Global potential biodiversity damage (BD_{Global}) – Aggregated values

Fig. 3 shows the Aggregated values for the damages of BD_{Global}. The results per functional unit of area for the production of 1 kg of soybean is more expressive for the Atlantic Forest ecoregion, followed by the Amazon, Pampas, Cerrado, Caatinga and Pantanal. The estimated impact for the Atlantic Forest is also higher than Average-country Brazil.

The Aggregated values for the BD_{Global} damage in the Atlantic Forest was of higher magnitude than those in Pantanal and the Caatinga. The Amazon and Pampas ecoregions have similar values, but about 53% less than the Atlantic Forest. Damages in the Atlantic Forest were also 32% higher than those of Average-country Brazil.

Fig. 4 shows that the Aggregated values for BD_{Global} according to the functional unit per total area of farming in each ecoregion, show that the Atlantic Forest is the ecoregion with the highest estimated damage, behind only Average-country Brazil. This result is similar to the functional unit of area needed for production (Fig. 3). Cerrado, Amazon and Pampas appear in decreasing order. The BD_{Global} of Average-country Brazil is higher than all the remaining.

The BD_{Global} Aggregated value for the Atlantic Forest is also higher than other ecoregions, mostly than Pantanal and Caatinga (99.65% higher). The Amazon and Pampas ecoregions have similar values, but about 81.27% lower than the Atlantic Forest. The value obtained for Average-country Brazil is about 48.13% higher than the Atlantic Forest.

Hence, to date, the Atlantic Forest is the ecoregion for which the highest damage was estimated, which was confirmed by using the two functional unit models.

3.2. Regional potential biodiversity damage ($BD_{Regional}$) – Aggregated values

The Aggregated values for $BD_{Regional}$ in which the functional unit is the area for production of 1 kg of soybean, is more relevant for the Atlantic Forest ecoregion, followed by impacts for the Amazon, Pantanal, Pampas, Caatinga and Cerrado, respectively (Fig. 5). Average-country Brazil damage is higher only than the Caatinga and Cerrado ecoregions.

The damage estimated using $BD_{Regional}$ Aggregated values for the

Table 4
Vulnerability Score (VS) values for the ecoregions and Regional Species Fragility Index (FI) for Brazil for each taxon expressed as potential loss of species per m^2, in cropland intense use.

Biomes	Ecoregions code[1]	Taxa[2]					
		Mamals	Birds	Amphibians	Reptiles	Plants	Aggregated
		Vulnerability Scores (VS)					
Amazon	NT0168	2,81E−02	1,73E−02	7,41E−02	4,11E−03	1,21E−02	–
Atlantic Forest	NT0150	5,85E−02	3,58E−02	8,21E−02	1,09E−02	8,82E−03	–
Caatinga	NT1304	7,10E−02	5,53E−02	2,89E−01	3,41E−02	7,51E−03	–
Cerrado	NT0704	1,20E−01	7,47E−02	2,27E−01	3,93E−02	8,55E−03	–
Pampas	NT0710	7,03E−02	2,15E−02	6,09E−02	1,36E−02	7,59E−03	–
Pantanal	NT0907	1,39E−02	8,83E−03	5,12E−02	5,47E−03	5,54E−03	–
		Index of Regional Fragility of Species (IF)					
Brazil	–	7,42E−03	8,72E−03	2,95E−02	6,16E−03	3,92E−03	–

Source: [1]WWF (2019); [2]Chaudhary and Books (2018).

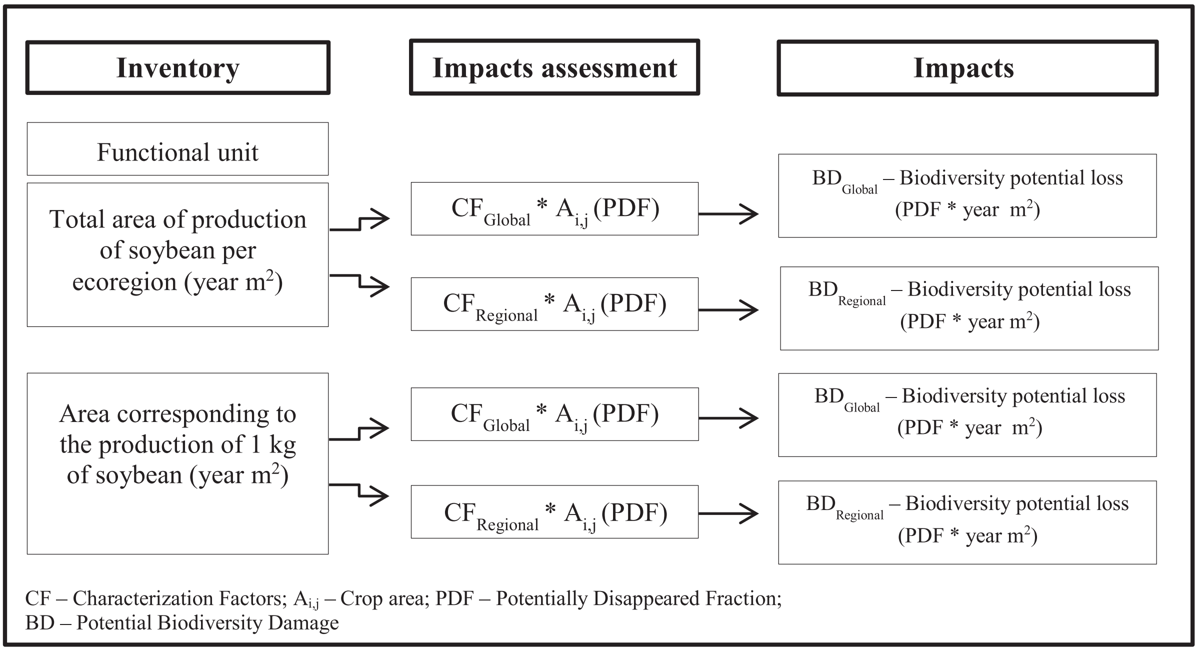

Fig. 2. Flowchart of the Life Cycle Inventory (LCI) and of the Potential Biodiversity Damage (BD) assessment in areas where there is soybean farming in Brazil.

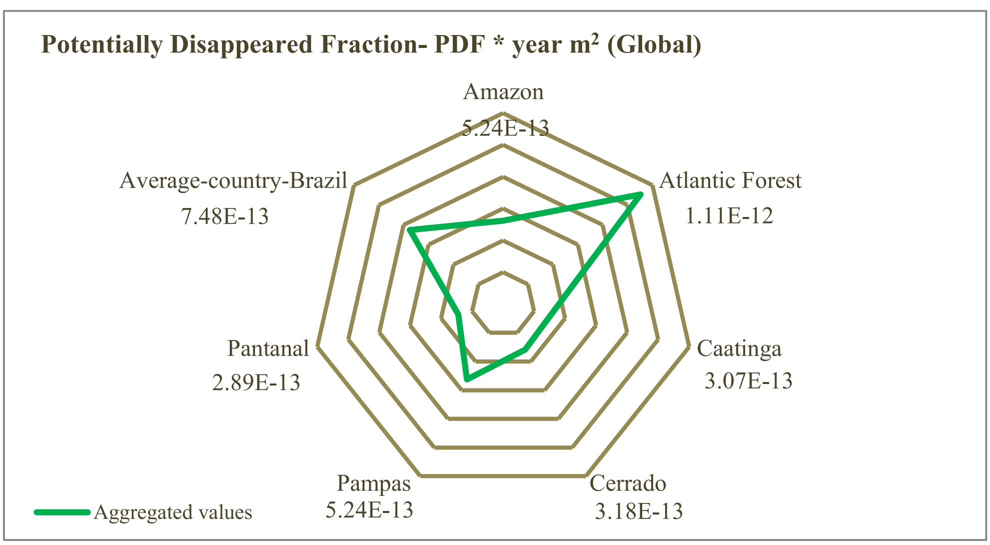

Fig. 3. Global aggregated values for Potential biodiversity damage (BD_{Global}) of the production of soybean in all ecoregions in Brazil – Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by area corresponding to the production of 1 kg of soybean (year m^2) as a functional unit.

Atlantic Forest is 6% higher than for the Amazon. Intermediate values are found for the Pantanal and Pampas ecoregions, 10% and 22% lower than the Atlantic Forest, respectively; while Caatinga and Cerrado are 73% and 80% lower, respectively. Brazil's Country Average values are 60% lower than the ones for the Atlantic Forest.

The results of the Aggregated values are higher for the Atlantic Forest than other ecoregions, only behind Average-country Brazil (Fig. 6), which corroborates the functional unit of total area of soybean production in each ecoregion. In sequence, in decreasing order of estimated impact, are the Amazon, Cerrado, Pampas, Pantanal and Caatinga. Only the potential damage for Average-country Brazil is higher than the one for the Atlantic Forest. Average-country Brazil damage is 12.71% higher than the one for the Atlantic Forest.

Overall, following the two functional unit models, biodiversity damage, according to the Aggregated values, affected the Atlantic Forest the most when compared with other ecoregions.

3.3. *Potential biodiversity damage (BD) – Taxa*

Regarding the assessment of functional units by extension of area for the production of 1 kg of soybean, the Atlantic Forest is the ecoregion that presents the highest damages estimated in BD_{Global} (Fig. 7) (for more information, see section 5). Below, the ecoregion performance is described in more detail in relation to the potential damages for each taxon.

The estimated BD_{Global} of mammals is higher for the Atlantic Forest ecoregion (30% higher than the Pampas – the second ecoregion with the highest BD_{Global}). The Amazon, Cerrado, the Caatinga and Pantanal come next. The highest birds BD_{Global} is also found for the Atlantic Forest, which was 46% higher than for the Amazon, followed by the Caatinga, Cerrado and Pantanal. The highest magnitude for BD_{Global} values were obtained for amphibians taxa which were 64% higher for the Atlantic Forest than the Pampas, followed by Cerrado, Caatinga, the

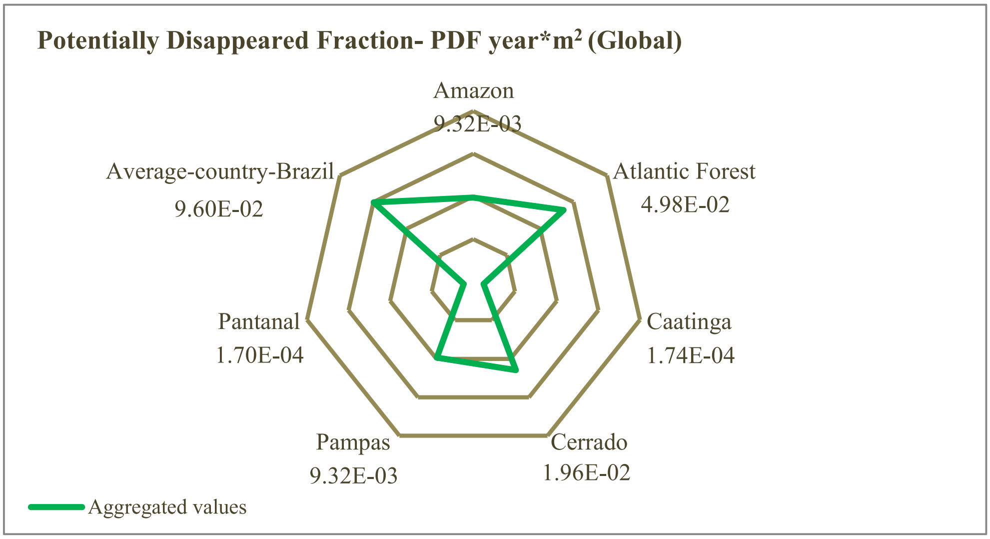

Fig. 4. Global aggregated values for Potential biodiversity damage (BD_{Global}) of the production of soybean in all ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – Average-country Brazil by area corresponding to the production of soybean (year m^2) as a functional unit.

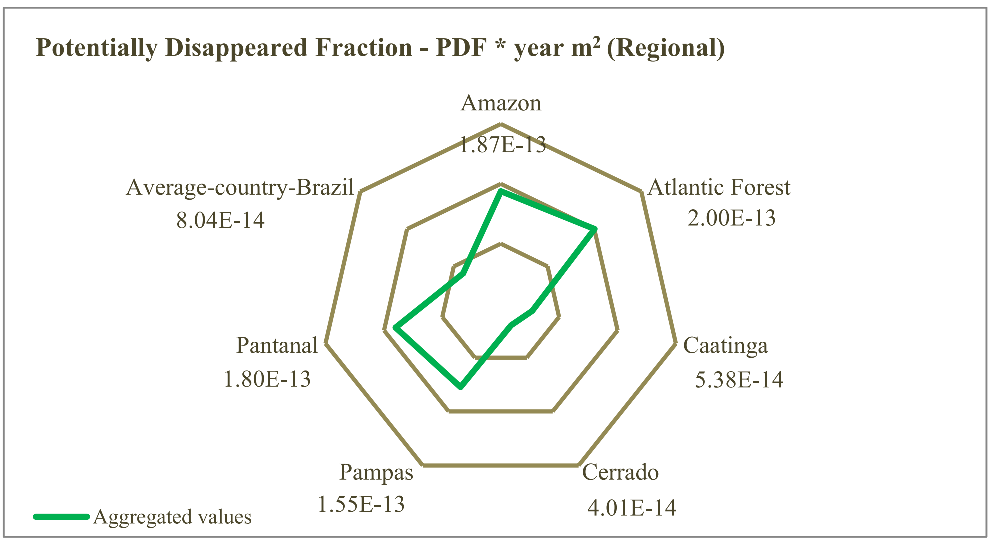

Fig. 5. Regional aggregated values for Potential biodiversity damage ($BD_{Regional}$) of the production of soybean in all ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by area corresponding to production to 1 kg of soybean (year m^2) as a functional unit.

Amazon and Pantanal.

However, reptiles BD_{Global} values are higher for the Pampas than the Atlantic Forest (12% higher). These are followed by Cerrado, Caatinga, Pantanal and the Amazon, in decreasing order. For plant taxon, the highest impact is found for the Amazon ecoregion, which is higher than the Atlantic Forest (25%), Pampas, Pantanal, Cerrado and Caatinga (decreasing order).

The BD_{Global}, when using CFs of Average-country Brazil, varies according to ecoregion for mammals, birds, amphibians and reptile taxa. BD_{Global} values correspond to the second highest damage. However, for plant taxa, BD_{Global} values constitute the highest.

Regarding $BD_{Regional}$, according to the same functional unit per taxon, results vary widely between ecoregions (Fig. 8). The highest $BD_{Regional}$ values for mammal taxa were obtained for the Pantanal ecoregion, which was 16% higher than for the Atlantic Forest, followed by the Amazon, Pampas, Caatinga and Cerrado. Regarding bird damage, the Amazon was the ecoregion in which the highest values were estimated – only 3% higher than Pantanal. Subsequently, the Atlantic Forest, Pampas, the Caatinga and the Cerrado appear in descending order.

For amphibian taxa, values were higher in the Atlantic Forest – 52% higher than than Pampas –, followed by the Pantanal, the Amazon, Cerrado and Caatinga. Regarding plant taxa, the highest values were also estimated for the Atlantic Forest, and were only 3% higher than for the Amazon, followed by Pampas, Pantanal, Cerrado and Caatinga. With regard to reptile taxa, the highest damage was estimated for the Pantanal ecoregion – 29% higher than the value found for the Atlantic Forest –, followed by Pampas, the Amazon, Caatinga and Cerrado, in decreasing order. The estimated values for Average-country Brazil are lower than for all ecoregions, except for Caatinga and Cerrado, for all taxa studied (Fig. 8).

The impact assessments per total area of production of soybean in each ecoregion as a functional unit are shown in Fig. 9. Among the ecoregions in which soybean is cultivated, the Atlantic Forest is the one in which the estimated BD_{Global} (all taxa) is the highest. The values for other ecoregions vary according to each taxon.

According to the functional unit, by total area of production of soybean in each ecoregion, the BD_{Global} for mammals is highest in the Atlantic Forest ecoregion, where it is 55% higher than in the Cerrado,

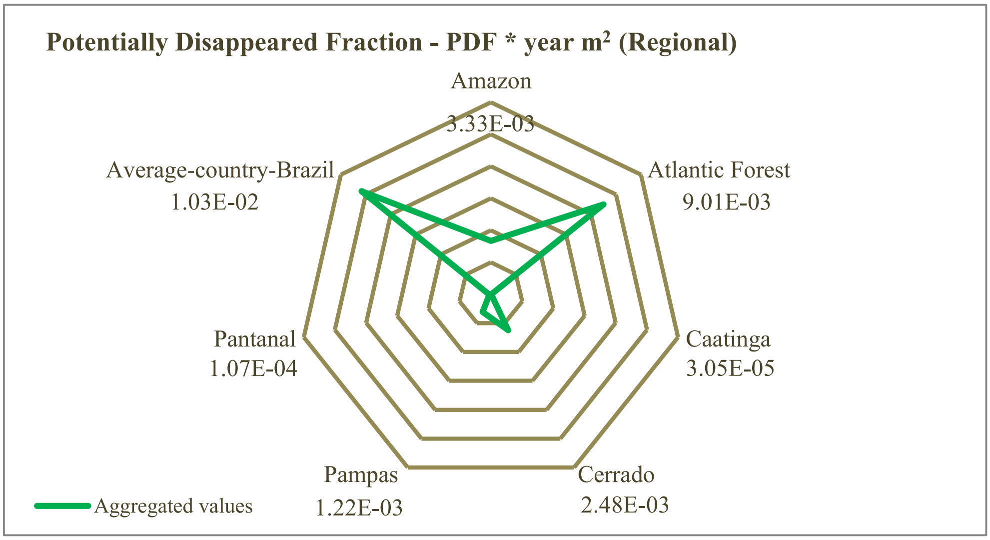

Fig. 6. Regional aggregated values for Potential biodiversity damage ($BD_{Regional}$) of the production of soybean in all ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal –, and Average-country Brazil by area corresponding to the production of soybean (year m^2) as a functional unit.

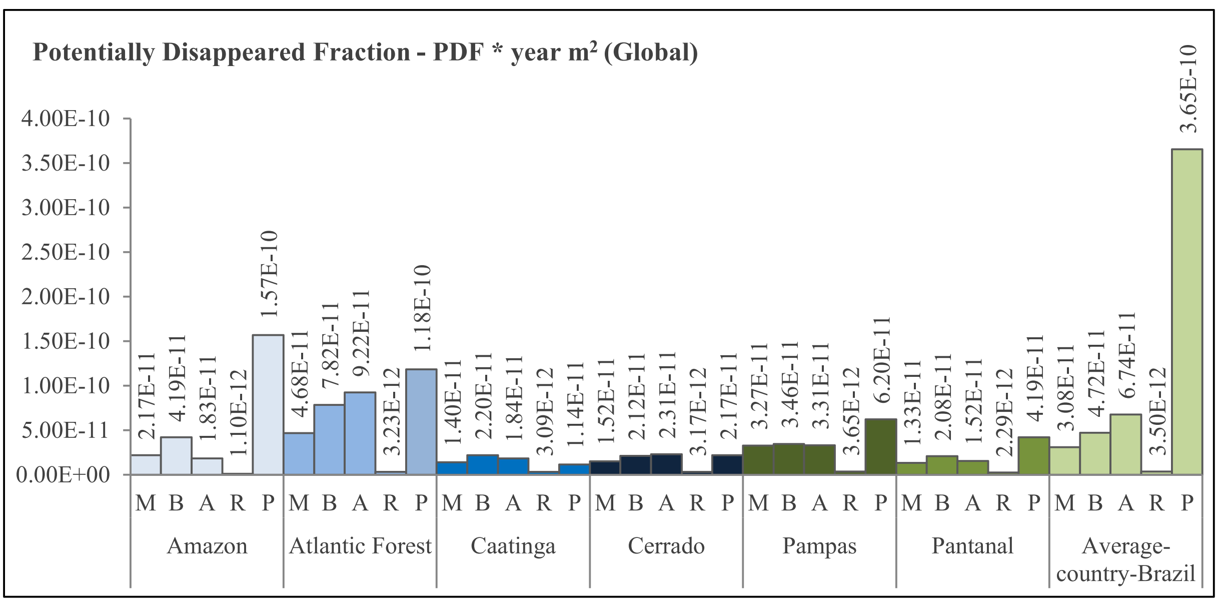

Fig. 7. Global potential biodiversity damage (BD_{Global}) for taxa – mammals (M), birds (B), amphibians (A), reptiles (R) and plants (P) – due to the production of soybean in six ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by area corresponding to production to 1 kg of soybean (year m^2) as a functional unit.

followed by the Amazon, Pampas, Caatinga and Pantanal. For bird taxon, the Atlantic Forest is also the ecoregion in which the highest damage was found, followed by Cerrado (63% lower), the Amazon, Pampas, Pantanal and Caatinga. The Atlantic Forest has the highest estimated BD for amphibian taxa (65% higher than the second ecoregion – Cerrado). The Amazon, Pampas, Caatinga and Pantanal come next, in descending order. For the reptile taxa, Cerrado was the ecoregion with the highest damage, about 25% higher than the Atlantic Forest, followed by the Pampas, the Amazon, Caatinga and Pantanal. The Atlantic Forest ecoregion presents the highest values for plant potential damage, which is 48% higher than the values found for the Amazon. The other ecoregions sorted by the value of their impacts are Cerrado, Pampas, Pantanal and Caatinga.

The estimated impacts for Average-country Brazil indicators present the highest BD_{Global} for all taxa in comparison with the ecoregions, mainly for plant taxa (Fig. 9).

The values obtained for the Atlantic Forest are the highest (for all taxa) when examining the $BD_{Regional}$, according to functional unit, for total area of production of soybean in each ecoregion (Fig. 10). The other ecoregions alternate in the order of impacts by taxon.

The highest $BD_{Regional}$ for mammals is in the Atlantic Forest, which is 61% higher than in the Amazon ecoregion. Decreasing damage is observed in the Cerrado, Pampas, Pantanal and Caatinga ecoregions. The highest damage for bird taxa was found in the Atlantic Forest, which was 56% higher than damage found in the Amazon ecoregion, followed by the Cerrado, Pampas, Pantanal and Caatinga. The Atlantic Forest is also the ecoregion with the highest $BD_{Regional}$ for amphibians, with values that are 87% higher than those found for the Cerrado ecoregion. The values fund for the Amazon, Pampas, Pantanal and Caatinga, listed in decreasing order, were assessed next. The Atlantic Forest ecoregion also presented the highest regional damage for reptile taxa, followed by the Cerrado, the Amazon, Pampas, Pantanal and Caatinga, in decreasing

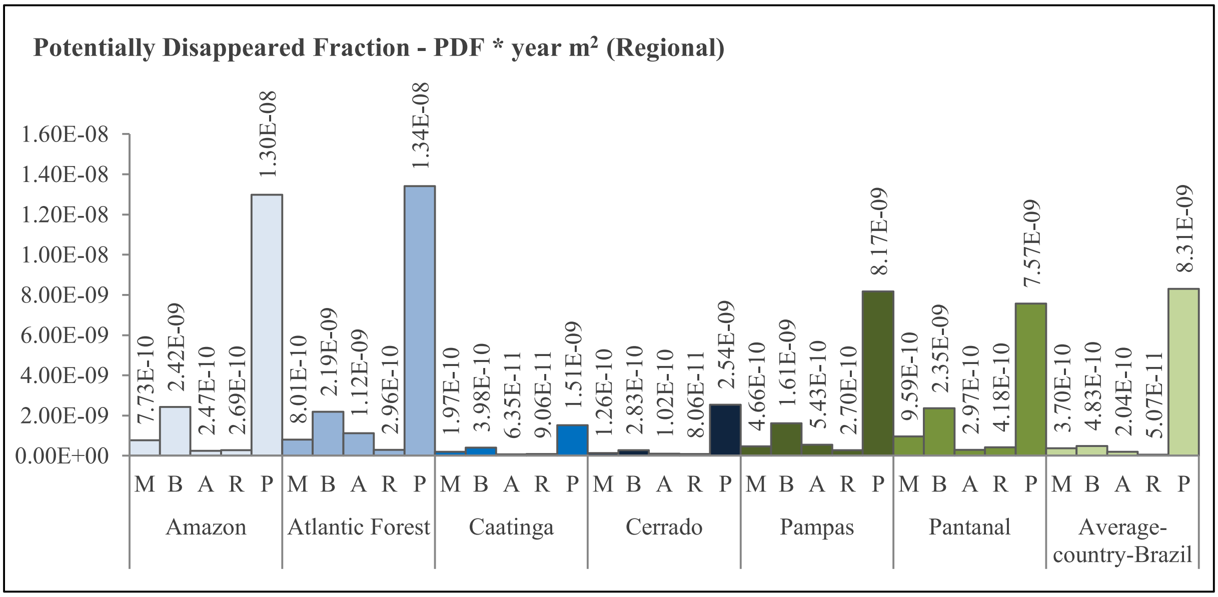

Fig. 8. Regional potential biodiversity damage ($BD_{Regional}$) for taxa – mammals (M), birds (B), amphibians (A), reptiles (R) and plants (P) – due to the production of soybean in six ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by area corresponding to production of 1 kg of soybean (year m^2) as a functional unit.

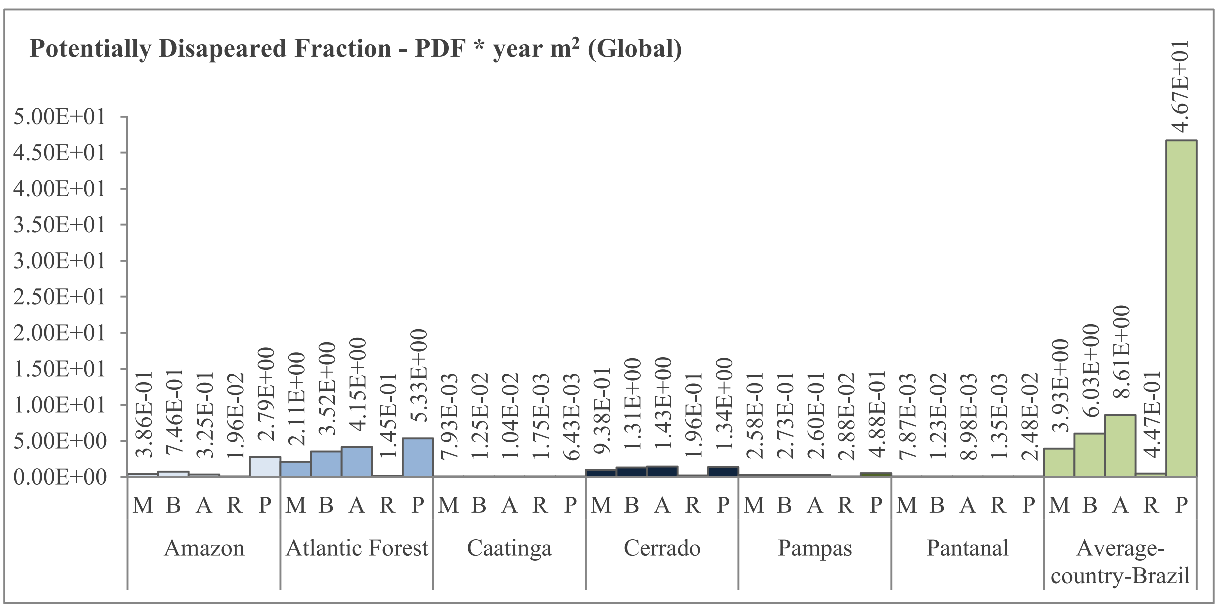

Fig. 9. Global potential biodiversity damage (BD_{Global}) for taxa – mammals (M), birds (B), amphibians (A), reptiles (R) and plants (P) – due to the production of soybean in six ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by total area of production of soybean for ecoregion (year m^2) as a functional unit.

order. The Atlantic Forest ecoregion values for plant taxa were by far the ones that depicted the highest potential damage (62% higher than the ones found for the Amazon). The Cerrado, Pampas, Pantanal and Caatinga come next.

CFs of Average-country Brazil showed that all the taxa presented higher estimated impacts than when assessed per ecoregion. However, the plant values were much higher than the CFs per ecoregion.

Hence, the Atlantic Forest is the ecoregion in which the highest damage values according to the $BD_{Regional}$ were found, regardless of the type of functional unit adopted. These findings are different from those observed for BD_{Global}, in which differences in the results were found according to the functional unit adopted. While the impacts on the Atlantic Forest were higher for both units in global assessments, for the regional ones this was true only when adopting the unit of total area of production of soybean for each ecoregion.

For the $BD_{Regional}$, expressed by the functional unit of area needed to produce 1 kg of soybeans, a distribution in the amount of potential damage in each taxon among the ecoregions was observed. For Pantanal and the Atlantic Forest, the highest $BD_{Regional}$ values were observed: mammals and reptiles in the Pantanal, and amphibians and plants in the Atlantic Forest.

Relevant values in potential regional damage were also observed in the Amazon ecoregion, and the highest values for bird taxa were estimated in this ecoregion. Overall, Caatinga and Cerrado were the ecoregions with the lowest $BD_{Regional}$ (four of the five taxa). Considering "crop area," the impacts to the Atlantic Forest were the highest found for

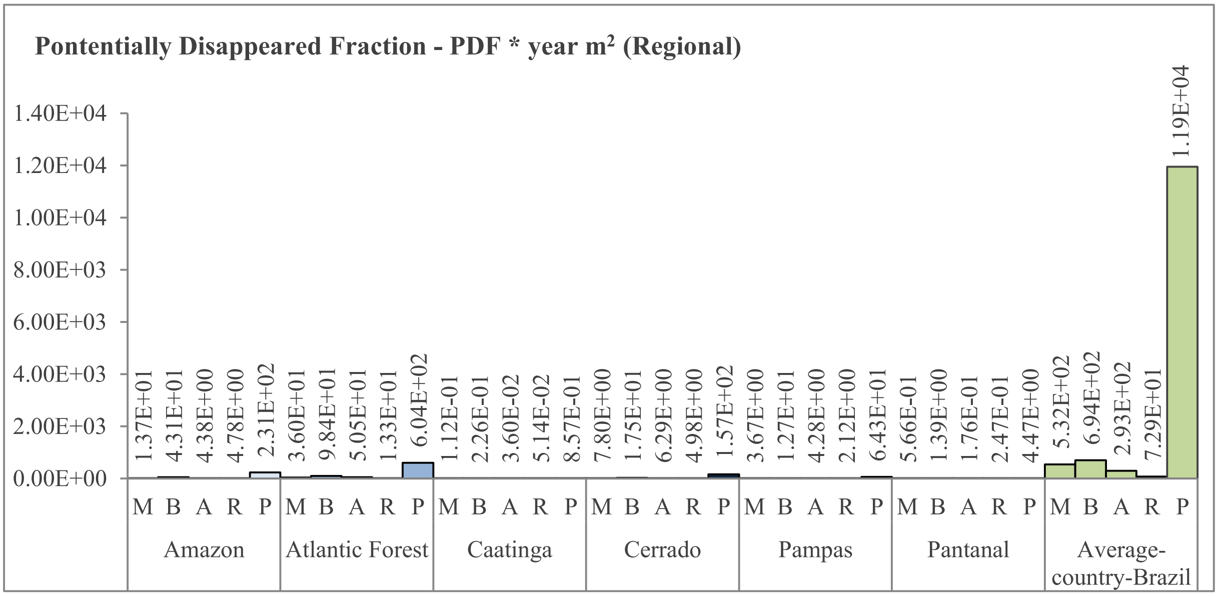

Fig. 10. Regional potential biodiversity damage ($BD_{Regional}$) for taxa – mammals (M), birds (B), amphibians (A), reptiles (R) and plants (P) – due to the production of soybean in six ecoregions in Brazil – the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal – and Average-country Brazil by total area of production of soybean for ecoregion (year m^2) as a functional unit.

all taxa.

While for the assessment of BD_{Global} according to the area needed to grow 1 kg of soybean, these results were observed due to the fact that the highest BD_{Global} for three of the five taxa under assessment here were found there: mammals, birds, and amphibians. The most relevant ecoregion for reptiles is the Pampas, and for plants, the Amazon. In the functional unit by extension of the cultivation area per ecoregion, the Atlantic Forest presented the highest damage impacts in four of the five assessed taxa: mammals, birds, amphibians, and plants. The ecoregions with the lowest BD_{Global} were the Pantanal and the Caatinga.

Differences between the results for BD_{Global} and $BD_{Regional}$ for all taxa were clearly observed, when considering potential biodiversity damage by functional unit, considering area for the production of 1 kg of soybean.

The differences between Global and Regional assessments for each taxon in each ecoregion surpass 90%. The lowest difference between them is for amphibians-Caatinga (71%) and amphibians-Cerrado (77%). Plant is the taxon in which the highest variations in results were found (about 99% in all ecoregions). Average-country Brazil assessment followed the same trend from those of taxa, with the lowest damage found for amphibians.

Divergent results between Global and Regional damage according to functional unit of total area for the production of soybean in each ecoregion were observed. The differences for each taxon, between Global and Regional BD, in all regions, surpassed 90%. The fewest differences between BD_{Global} and $BD_{Regional}$ were observed for amphibians-Caatinga (71%) and amphibians-Cerrado (77%). The highest differences were observed for plant taxa (98 to 99% in all ecoregions). Similar results were observed for Average-country Brazil (lowest values for amphibians – 97 to 99%).

Therefore, the impacts of the production of soybean in Brazil to biodiversity, in all taxa, was always more expressive at the regional than global level.

4. Discussion

The results found in this study evidence that the potential damage to species per taxa according to the BD_{Global} due to soybean cultivation, regardless of the functional unit adopted, was more relevant in the Atlantic Forest ecoregion, in which the highest values of total species richness (S_{org}) were observed (for S_{org} values, see Chaudhary et al., 2015; Chaudhary and Books, 2018), followed by the Amazon. Furthermore, the Atlantic Forest is an ecoregion with a high extent of crop areas in Brazil, but the Cerrado has the greatest extension of soybean farming areas, and even the Cerrado presents a higher productivity and lower characterization factors than the Atlantic Forest. Thus, the potential damages, determined by the aggregated values, were consistent with those from the BD_{Global}, which also show the Atlantic Forest as the ecoregion with the highest potential damage, followed by the Amazon and the Pampas.

This results may be explained by the CFs, according to Chaudhary and Books (2018), which consider the Vulnerability score (VS) of the species by land use and change (cultivation, pasture, forest, urban). It represents the affinity of each species with different environments [IUCN Red List Habitat Classification Scheme (IUCN, 2015)], and their purposes with the new function when transformed.

The species affinity with environments – VS – and their ability to interact with different types of land use are determinant for its preservation. The bird *Passer domesticus* inhabits plenty of environments with different land uses. It exhibits low affinity with specific sites, which implies that its risk of extinction due to environmental change is minimal. However, the wolf *Chrysocyon brachyurus* inhabits only grasslands, swamps and savannas, but is not associated with degraded forests or even urban sites. The anteater *Myrmecophaga tridactyla* also only inhabits degraded savannas and forests and cannot survive in any other type of land modified by anthropogenic activity. The ability of a species to inhabit a specific type of land depends on its biophysical characteristics and life history, such as food availability, body size, temperature range, etc. (IUCN, 2015).

As a second point, it was observed that the $BD_{Regional}$ per taxon, even when following different inventory models, had great variation among estimated damages for each taxon. For the modeling by area required for the production of 1 kg of soybean, Pantanal and the Atlantic Forest were the ecoregions in which the highest $BD_{Regional}$ were found, while the lowest were those from Caatinga and Cerrado. When modeling by total area of cultivation of soybean in each ecoregion, the highest damage values were observed in the Atlantic Forest for the five taxa.

The potential damage, determined by the $BD_{Regional}$ by aggregated values, differed from the results of the $BD_{Regional}$ by taxa. But the highest potential damage according to both models was also observed for the

Atlantic Forest.

Regarding regional damages, results were also influenced by the divergent values of the different functional units, besides the parameters composing the indicators. The highest CF values were those obtained for the Atlantic Forest and Pantanal ecoregions. However, the VS values obtained for these ecoregions were the third and fifth highest, respectively.

The third point we can argue is that the use of VS to assess the FI is relevant, as hypothesized by the present study. Applying the indicators to use the FI in assessments, in addition to being practical and efficient, allows their dissemination for diagnostics and action measures at administrative geographical levels, taking into consideration ecoregions, that is, the natural geographical levels of the country. Thus, the change in equation suggested in this paper can be applied to other sites.

In a fourth point, the results of the $BD_{Regional}$ of the ecoregions are different from the results of the BD_{Global} for all taxa and aggregated values. This difference is mostly due to the inclusion of the VS value in the equation. The highest VS value was obtained from amphibian taxon, followed by mammals, birds, and subsequently – alternating their positions according to ecoregion –, reptiles and plants. When analyzing the VS values by ecoregion, the highest values were frequently obtained in the Cerrado ecoregion.

According to Chaudhary et al. (2015), to determine VS values, we must take into account the endemic richness of each taxon for each ecoregion. This richness can be interpreted as the region's specific contribution to global biodiversity. So when VS value is 1 for all species that inhabit a specific ecoregion exclusively ("strictly endemic"), they are listed as "critically at risk" (IUCN Red List Habitat). The highest CF values found for the Cerrado ecoregion indicate, proportionally, more endemic species in this ecoregion.

This duality was also described previously when Chaudhary et al. (2015) assessed ethanol production in Brazil (sugarcane), France (beet) and the USA (corn). Their results diverged according to BD_{Global} and $BD_{Regional}$. The differences were caused by the relatively high VS values for species endemic in Brazilian ecoregions when compared to France and USA ecosystems. Consequently, $CF_{Regional}$ indicated that production in France was the most harmful while, CF_{Global} indicated Brazil.

As a fifth point, the impacts of the CFs of Average-country Brazil are different between BD_{Global} and $BD_{Regional}$. High potential damages were observed for Global BD mostly for plant taxon. The damages found for Average-country Brazil, in general, were higher than all the ecoregions, including the Atlantic Forest. Hence, when using Average-country, questions about assessment increase, which indicates this is not a suitable option for choosing CF, although it is the most practical option.

Finally, the findings presented here demonstrate that assessments by taxa are much more efficient and, whenever possible, should be adopted. The choice of functional unit significantly influences the results. The production of soybean in Brazil causes more damage to biodiversity in the Atlantic Forest ecoregion, although the other ecoregions are also impacted, and the damage is more relevant regionally than globally. Palliative measures, technical and/or political, must be adopted aiming to reduce and avoid damages.

Regarding global damage, for those ecoregions which encompass more than one country and harbor vulnerable endemic species, shared responsibility must be taken to reduce loss of species.

Technical actions which enhance crop productivity may contribute to reduce biodiversity by reducing deforestation pressure. The adoption of extensive or semi-intensive farming, crop rotation, integrated farming systems (crops, livestock and forest) should be prioritized. However, political measures, when fulfilled, may be even more effective due to the standardization of means to preserve different ecoregions throughout the country.

The Brazilian Forest Code – Law no. 12.651/2012 – (Brasil, 2012) includes articles regarding the Protection of Native Vegetation (*Área de Preservação Permanente*) – art. 3, §2 – and Permanent Protection Area (*Área de Proteção Permanente*) – art. 3, §2. These articles aim to ensure the maintenance or restoration of natural vegetation throughout farms to protect not only biodiversity, but natural resources, in general.

Art. 1-A, of Law no. 12,651/2012 establishes general rules for the protection of vegetation, Permanent Preservation Areas and Legal Reserve Areas. Forest exploitation, supply of forest feedstock, control of the origin of forest products and control and prevention of forest fires are also regulated. Moreover, the law provides the economic and financial instruments to achieve its objectives.

To this end, §1 affirms Brazil's sovereign commitment to the preservation of its forests and other forms of native vegetation, as well as biodiversity, soil, water resources and the integrity of the climate system, for the well-being of present and future generations. On the other hand, § 2 reaffirms the importance of the strategic function of agricultural activities and the role of forests and other forms of native vegetation in sustainability, economic growth, improvement of the quality of life of the Brazilian population and the country's presence in national and international markets of food and bioenergy.

Art. 12 imposes that every rural property must maintain native vegetation coverage, as a Legal Reserve, observing the following minimum percentages in relation to the total area of the farm:

I - Located in the Legal Amazon: a) 80% in farms located in a forest area; b) 35% when located in the Cerrado vegetation; c) 20% when located in general fields.

II - Located in other regions of the country: 20%.

Legislative actions can guarantee, when followed, that biodiversity spreads throughout the national territory without compromising agricultural production and development of the national economy. Despite "strict environmental legislation," deforestation and forest fires in Brazil ecoregions remain unsolved. A recent study that assessed the period from 2008 to 2020 evidenced that illegal deforestation concentrates in the Cerrado and Amazon biomes, and just 2% of proprieties cause 62% of the potentially illegal deforestation (Rajão et al., 2020). Although these areas encompass huge extensions of land, these data evidence that not only the legislation but measures that warrant the laws to be followed must be a real priority.

Legislative actions ensure the preservation of biomes and their biodiversity, and technical actions must be taken so that there is balance between environmental preservation and agricultural production. For this, the LCA methodology is one of the principal alternatives, because it attributes environmental impacts to products, generating information to improve environmental performance.

The application of this case study did not take into account the total inventory of the life cycle and possible impacts on land transformation, because indicators are still under development. This would constitute a new endpoint category, still to be defined, possibly requiring a new category: Biodiversity. Thus, future definitions will be established for the impact category framework and the elaboration of complete case studies to test the robustness of the CFs.

5. Conclusions

The findings reported in this study, which analyzed the levels of different amounts of species lost in areas where soybean is cultivated in Brazil in relation to the indicators BD_{Global} and $BD_{Regional}$, highlight a great occurrence of endemic species in these ecoregions.

When using BD_{Global}, the highest potential loss was found for the Atlantic Forest ecoregion, especially for plants, mammals, birds and amphibians taxa, respectively. For reptiles and plants, the highest losses were found in the Pampas and the Amazon. BD_{Global}, analyzed by taxa or by aggregated values, corroborated findings for the same ecoregions. However, results lead to different classifications when facing the amount of potential loss of species. We suggest that when the study does not intend to specify the taxa results, aggregated values are suitable; however, if the proposed study requires greater precision, assessment according to taxa is suggested.

Regarding $BD_{Regional}$, ecoregions were ranked according to higher potential of loss of species depending on the taxa. The difference between BD_{Gloral} and $BD_{Regional}$ is related to values attributed to Vulnerability Scores (VS). Overall, the Atlantic Forest was pointed as the ecoregion to potentially suffer the most biodiversity damage among Brazilian ecoregions due to its number of species and endemic richness. Considering the great historic reduction of the area of this ecoregion and, consequently, of its natural biodiversity, not only preservation must be a priority, but also regeneration. However, relevant losses in other ecoregions, where natural vegetal coverage has been replaced by soybean croplands, must be considered.

For damage mitigation, technical and political measures should be adopted. Political ones have been suggested as the most efficient to diminish the impact on biodiversity.

About the use of the Regional Special Fragility Index (FI), it was relevant for diagnosing action measures at administrative geographical levels, considering only the ecoregions present in a country. Thus, the FI suggested in this paper can be applied to other sites.

Therefore, the indicators of biodiversity loss applied in the present study have shown they are suitable to perform an overall assessment, which allows the detection hotspots. However, for the practical application of political decisions/solutions, it would be more efficient if they reflected different production systems and country vulnerabilities in more detail. Thus, next steps in the development of biodiversity damage assessment must include the influence of different management practices in agricultural production systems.

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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