The economic risk of the losses in pest control as frogs decline

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Abstract

Crop pests threaten agricultural productivity, causing significant economic losses and food security issues. Although various control methods exist, pesticide reliance raises health and environmental concerns. In this sense, the Integrated Pest Management (IPM) is a favored approach that minimizes pesticide use while incorporating diverse pest control methods. A key aspect of IPM is biological control, which employs organisms to mitigate pests. However, the potential of certain groups like amphibians in pest suppression is understudied. Our study in Brazil estimates the annual pest control value provided by anurans by combining empirical data, allometric estimates, and spatial analysis. We estimate the value of natural control of native pests in Brazilian crops to be 23.6 billion dollars annually, with the value of natural control attributable to anurans to be $1.18 billion annually for all crops and nearly half a million only for soybean cultivated in Central Brazil. Frogs alone have the potential to reduce the population of invertebrates that may be considered harmful to crops by nearly 300 million individuals annually. Despite this biodiversity-driven biological control being crucial for ecosystem health and agricultural productivity, land use changes and climate change pose threats to these vital functions, leading to the increase of economic losses and food insecurity.

Key-words: Amphibians, biological control, crops, Integrated Pest Management.

Graphical abstract

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Introduction

Controlling insect pests is a major challenge for agriculture worldwide, and biological control and integrated pest management are widely acknowledged as cost-effective strategies to prevent and mitigate this issue (Stenberg 2017). Humans compete with crop pests for agricultural resources, especially when high-input monoculture is practiced over large areas (Oerke and Dehne 2004). Crop pests, which include animal pests (e.g., insects, mites, nematodes), plant pathogens (e.g., viruses, bacteria, fungi), and weeds (i.e. competitive plants), reduce the yield and quality of agricultural production, causing substantial economic losses and reducing food security at household, national, and global levels (Savary et al. 2019). Yield losses result in reduced productivity, leading to a smaller yield per unit area, while qualitative losses from pests may result in the reduced content of valuable ingredients, reduced market quality, or due to the contamination of the harvested product with pests or toxic products of the pests (Oerke 2006). In a recent study, Savary et al. (2019) provide numerical estimates for the yield losses caused by pests on five major crops worldwide (i.e., wheat, rice, maize, potato, and soybean). They found that global crop losses caused by pests range between 17 and 30%.

Different pest control strategies, including harmfull for both pests and humans as pesticides (Boedeker et al. 2020), play a critical role in reducing diseases and increasing crop yields worldwide (Tudi et al. 2021). Integrated pest management (hereafter IPM) is the officially endorsed paradigm for crop protection (Stenberg 2017). In summary, IPM is a multi-faceted approach drawing on available methods to control plant pests, with minimal use of pesticides (FAO 2023). The concept was initially developed by entomologists faced with indiscriminate broad-spectrum insecticide use and insect outbreaks caused by the elimination of natural enemies and the emergence of pesticide resistance (Barzman et al. 2015). The theoretical basis of this method is that different pest management strategies interact with each other, having synergetic effects when used together, which can improve the results if compared to those used alone (Barzman et al. 2015, Stenberg 2017). It builds on agronomic, mechanical, physical, and biological principles, resorting to selective pesticide use when addressing situations that cannot be successfully managed with other tools (Barzman et al. 2015). Essentially, the elements that form the basis for ecology-based IPM involves plant vaccination, intrinsic heritable plant resistance, biorational synthetic volatiles, biological control, inter and intra specific botanical diversity (Stenberg 2017).

One important facet of IPM is biological control, which is the use of organisms to reduce the population density or impact of pests. Biological control is probably the most well-researched element of the IPM concept and root of some of the most innovative practical applications. Usually, arthropods are mainly controlled using predators, parasitoids, and pathogens, while plant pathogens are mainly combated using antagonistic microbes. An increasing number of studies have focused on the role of bats as natural enemies of agricultural pests (see review on Tuneu-Corral et al. 2023). For example, in an exclusion experiment, Beilke and O'Keefe (2023) showed that insectivorous bats drove top-down trophic cascades, playing an integral role in forest ecosystems. They demonstrate that insect density was three times greater on seedlings in bat-excluded versus control plots and that seedling defoliation was five times greater with bats excluded in the Yellowwood State Forest, US. In the Brazilian Cerrado, using a conservative estimation, researchers found that bats saved US$ 94 per hectare of cornfields, accounting for annual savings of US$ 390.6 million per harvest (Aguiar et al. 2021). Besides bats, other vertebrates and invertebrates are known to suppress crop pests, such as insectivorous birds (Nyffeler et al. 2018), mammals, reptiles, amphibians (Civantos et al. 2012) and other insects (Losey and Vaughan 2006, Daniels et al. 2017).

However, IPM directly addresses organism interactions, which are often poorly studied in many parts of the world, particularly in the Neotropics (Dáttilo and Rico-Gray 2018). Among the various vertebrates with the potential to prey on crop pests, amphibians are well-known for their consumption of numerous arthropods, exhibiting a broad range in their diet (Ceron et al. 2019). Nonetheless, we are just beginning to comprehend the ecological significance of amphibians as their populations decline and they disappear from many regions of the world due to disease, habitat loss, climate change and alteration, along with fertilizer and pesticide stressors (Blaustein et al. 2003, Whiles et al. 2006, Luedtke et al. 2023). Amphibians play a key role in energy flow and nutrient cycling in both aquatic and terrestrial environments (Valencia-Aguilar et al. 2013). Tadpoles can account for a substantial component of consumer biomass in tropical headwater streams and thus have the potential to influence basal resources by altering algal communities, affecting patterns of primary production, and organic matter dynamics (Colón-Gaud et al. 2010). Tadpoles also compete with mosquito larvae for oviposition sites (Mokany and Shine 2003) and reduce their populations by direct mosquito larvae predation (DuRant and Hopkins 2008, Bowatte et al. 2013, Salinas et al. 2018, Perrin et al. 2023). In the adult stage amphibians can consume great amounts of arthropods, including crop pests (Attademo et al. 2005, 2007b) and disease vectors (Peltzer and Lajmanovich 2002), regulating prey population dynamics and altering disease transmission and pest outbreaks (Hocking and Babbitt 2014). Based on their predatory functions in both life stages, amphibians play a crucial role in ecosystem regulating services through their biological control (Hocking and Babbitt 2014). The potential role of amphibians in biological control, has been shown in a few correlational studies. Amphibian decline due to the fungal pathogen *Batrachochytrium dendrobatidis* (*Bd*) has been associated with an increase in malaria cases in Central America (Springborn et al. 2022). In Argentina it has been shown that ca. 73% of amphibian's diets are composed by arthropods harmful to crops (Attademo et al. 2007a).

Despite the few studies suggesting the importance of amphibians in biological control, we still have a poor quantitative understanding of the potential of amphibians as natural agents of biological control and there are no estimates of the economic value of amphibians to pest control. Here we use empirical studies on anuran diets in Brazil, allometric estimates and spatial analysis to estimate the annual amount of invertebrates consumed by anurans and estimate the annual value of pest control services provided by them.

Material and Methods

Anuran diet

To determine anuran diets we sampled anurans and arthropods in 19 ponds in Mato Grosso do Sul, central Brazil during the wet and dry seasons. For further details on sampling and sampling locations, see Ceron et al. (2020, 2022). We analyzed the stomachal content of collected anurans under a stereomicroscope and classified each item into operational taxonomic units (OTUs). This classification was employed because arthropods were usually partially digested. The taxonomic unity was usually Order, except for the families Formicidae (Hymenoptera) and Ixodidae (Ixodida). Larvae were included as separate OTUs (e.g., Lepidoptera, Lepidoptera larvae). After measuring the length and width of each prey, we estimated their volumes using the formula of the ellipsoid (Magnusson et al. 2003), where, V = volume, W = width, and L = length:

$$V = \frac{4}{3} \times \pi \times \frac{L}{2} \times 2 \left(\frac{W}{2}\right)^2$$

Estimating annual prey consumption

We used the maximum number of items and volumes consumed per sampled species to estimate the total number (or volume) of prey ingested by an anuran community during a year. To extrapolate local estimates of consumption to larger spatial and temporal scale and obtain and annual index of prey consumption we multiplied the mean number (or volume) of ingested prey by anuran species, the mean of days that anuran are active in a year, the anuran rate of consumption, anuran population size, and community size. Thus, our assessment is based on the following assumptions:

Assumption 1: Anuran activity was based on the reproductivity period of each species in the state of Mato Grosso do Sul obtained from the literature (e.g., Prado et al. 2005, Sousa et al. 2019). Reproductive activity patterns exhibited by species were classified as (1) continuous: species with individuals reproducing throughout the year or more than six months; (2) prolonged: species reproducing for more than three consecutive months until six months, and (3) explosive: species with breeding activity lasting one or a few days (less than three months) (Wells, 2007).

Assumption 2: Because anurans are ectothermic animals, their activity depends most on abiotic factors, mainly the temperature (Wells 2007), so as a proxy of anuran activity, we used the relative temperature (°C) during the calling behavior of two widespread Neotropical frogs (*Pseudis platensis* and *Boana raniceps*) monitored in the southern Pantanal wetlands in Brazil (Bonnefond et al. 2020). For these species, the temperature of calling activity ranged from nine to 37ºC (mean 24.7ºC). Thus, for the years 2018 and 2019 (when anurans were collected), we counted the number of days where the minimum and maximum temperatures of sampled municipalities fall inside the range of anuran-calling activity during the dry and the rainy season [temperature data obtained in CEMTEC/MS (https://www.cemtec.ms.gov.br/)]. Thus, for continuous breeders, we find suitable temperatures for a mean of 350 days in a year, the prolonged breeder may be active for a mean of 175 days in a year, and the explosive breeders may be active for 88 days during a year.

We also assessed the length of the time interval over which anuran stomachs were filled and emptied based on previous studies and extrapolated this number to the sampled species (range from 6h to 48h, mean 24h).

Assumption 3: The time that the food takes to travel the digestive tract is considered an indirect measure of the rate of digestion, which includes the time required for digestion, absorption of nutrients, and the time needed to move the bolus through the digestive tract (Dorcas et al., 1997). There are a few studies investigating passage rate in amphibias. Kirkland (1904) verified that the toad's stomach (Bufonidae: *Anaxyrus americanus)* is practically filled and emptied four times each twenty-four hours (6h). For *Acris blanchardi* (Hylidae), Johnson and Christiansen (1976) concluded that these frogs consume enough food items to fill their stomachs three times per day (8h). To *Pelophylax lessonae* (Ranidae) time passage throughout the digestive tract involves 12h (Root 1961). Frost (1932) observed that in laboratory-caged *Rana clamitans* and *R. sylvatica* (Ranidae) the food passed through their digestive tracts in two days (48h). For *Pleurodema nebulosum* (Leptodactylidae) the time that food takes to travel the digestive tract is 45h (Sanabria et al. 2020). So, we used the mean of the time passage throughout the digestive tract from this literature and extrapolated this measure to sampling species.

After that, using the proportion of ingested prey by OTUs in sampled anurans, we estimate the number and the volume of OTUs ingested by populations/year.
Assumption 4: The anurans' population size was assigned based on Damuth's law (Damuth 1987), assuming that density of the population scales according to body size (Figure S1). The relationship between a species' density (d) and its body mass (m) is often expressed as a power law, $d = cm^k$, where c is a constant for a given variable and k is a dimensionless scaling exponent. Consistent with prior works we attributed the −3/4 value to the scaling exponent (Hatton et al. 2019) and because the majority of anuran populations are density dependent (Leão et al. 2018). As a result, we established a mean density of a sampled anuran population as 0.84 ind/m², inside a range of 3.39^{-8} (for Pepper Frog – *Leptodactylus labyrinthicus*) and 3.24 ind/m² (for Brown-bordered Snouted Treefrog – *Scinax fuscomarginatus* We used an additional method to assign abundances based on the the log-normal frequency distribution (mean 3.59 ind/m²), once many of the best-sampled communities tend to exhibit a log-normal abundance distribution (Brown 1984). We chose to use the estimates obtained from the Damuth's law because the range of population densities fall within the range of densities found in empirical studies carried out with anurans around the world (see supplementary material in Santini et al. 2018).

After that, using the number and volume of ingested prey by anuran populations, we estimate the size of an anuran community. **Assumption 5:** Anuran community size was estimated based on the mean of community size sampled (e.g., Ceron et al. 2020).

Pest control

To valuate the ecosystem service derived from the predation of invertebrates by anurans we calculate the value of anuran biological control following the formula proposed by Losey and Vaughan (2006):

$$V_{ni} = (NC_{ni} - CC_{ni}) \times P_i$$

where, *V* is the value of anuran biological control, *CC* is the cost of damage caused by insect pests at current levels of control (*CC*), *NC* is the cost caused by insect pests if no controls were functioning and, P_i is the proportion of pests that are controlled by anurans as opposed to other mechanisms (e.g., beneficial insects, pathogens or climate):

Because of data limitations, we restrict our estimate to the value derived from the suppression of insect pests that attack crop plants. Anurans suppress populations of insects that attack both humans and livestock, but there is note enough available data to obtain realistic estimates of the value of these services. As with the rest of our analysis, we also limit our calculations to pests and anurans native to Brazil. Nonetheless, it is important to highlight that such decisions make the following modeling more caution. Our first step was to calculate the cost of damage due to insect pests at current levels of control from natural antagonists. Drawing on previously published estimates, Oliveira et al. (2014) presented monetary values for the total production of major crops grown in Brazil per year, including losses related to direct damage caused by pests ($14.73 or 7.7% annually). The loss of $14.73 billion includes damage both from native pests that originated in Brazil and from exotic pests that originated in other countries. Of this total, about 13.7% are caused by alien species (Oliveira et al. 2013), totaling $2.01 billion in losses. Therefore, we assume that native species are responsible for 86.3% of the cost of damage from all pests in Brazil. Hence, we estimate that the cost associated with native pest species at current levels of suppression by natural enemies is 86.3% of

$14.73 billion, or $12.71 billion. We designate this value current control by native insects (CC_{ni}).

To complete our estimation of the value of pest control, we needed an estimate of the cost of damage due to insects in the absence of the control service. Specifically, Calkins (1983) found that only 35% of the exotic pests in the United States are pests in their home range. Extending this finding to Brazil, we assume that the same relationship holds true, and thus only 35% of potential insect pest species that are native to Brazil reach damaging levels. In other words, we assume that 65% of the potential damage from native pest species is being suppressed and that 65% of the potential financial cost of this damage is being saved. Based on these assumptions, we estimate that the $12.71 billion lost annually to native insect pests (CC_{ni}) is 35% of what would be lost if natural controls were not functioning. If no natural forces were functioning to control native insect pests, we estimate that they could cause $36.31 billion in damage in Brazil each year (NC_{ni}). By subtraction, the value of pest control by our native fauna would be approximately $23.6 billion.

Evidently, not all of this value for the natural control of insect pests is attributable to anurans. The majority of pest suppression comes from other causes, such as predator insects, pathogens, climatic events, and host-plant resistance. Therefore we conservatively estimate a maximum of 5% of the total pest control by anurans. Thus, using this average (5%), we estimate the value of natural control attributable to anurans.

Brazilian Cerrado as a study case

The Brazilian Cerrado, the second-largest biome in Latin America, spans over 200 million hectares and serves as a hub for highly intensive agricultural activities, particularly in grain and beef production (Klink and Machado, 2005). This biome has already experienced a 50% loss in its natural vegetation cover, with only 11% of the area designated as protected zones or Indigenous lands (Sano et al., 2019), while a significant portion, precisely 99 million hectares or 50% of the Cerrado's original area, has been transformed into farmlands and pastures (MapBiomas, 2023).

Large-scale monoculture favors the spread of crop pests, which can reduce crop production by 43% (Oliveira et al., 2014). In central Brazil, where the Cerrado biome once thrived, the impact of crop pests on yield mirrors the national trend. While specific data on yield loss in the Cerrado due to pests is lacking, it's crucial to note that the Cerrado region serves as the epicenter of Brazil's soy industry. In 2020, it accounted for nearly half of the country's soy production, totaling 52 million tons, across approximately 15 million hectares of land (WBCSD, 2023). Given that soy loss in Brazil averages around 5% annually, this results in five dollars lost per hectare (Oliveira et al., 2014).

Anurans inhabiting natural and artificial ponds in the Cerrado can contribute to pest control. Because most anurans require water bodies to reproduce we focused on these types of habitats to estimate the potential of pest suppression related to frogs in the Cerrado region. We first identified and filtered lentic water bodies in Cerrado, using a shapefile provided by National Water Agency (ANA 2020). After that, based on the coverage of each pixel by lentic water bodies, we estimated the density of anurans in each cell (following Damuth’s law) and extrapolated the number and volume of consumed prey by sampled communities to each pixel (55 km of resolution) according to habitat availability, using methods described in detail in the *Estimating annual prey consumption* section below.

We also estimated the annual savings due to biological control in soybean crops and the potential savings attributable to anurans' pest control in soybean crops. Using a raster of soybean coverage in Cerrado during 2013–2014 provided by Global Forest Watch (GFW) (https://data.globalforestwatch.org/datasets/gfw::soy-in-cerrado-biome/about), yield per hectare (CONAB 2024), average of real to dollar exchange between 2020–2023 (IPEA 2024), average minimum value of soybeans 60kg bag between 2020–2023 and crop losses attributable to soybeans crop (Oliveira et al. 2014), we estimate the annual savings due to biological control in soybean crops. We also masked the lentic water bodies' shapefile with the soybean coverage raster in Cerrado and calculated the potential savings attributable to anurans' pest control in soybean crops based on a buffer around lentic water bodies' of 2km (considering the range area of amphibians), and the same procedure mentioned above.

All analyses were performed in the R environment (R Core Team 2023) using *raster* (Hijmans and Van Etten 2016), *terra* (Hijmans et al. 2022), and *sf* packages (Pebesma 2018), with a 55 km resolution.

Results

Considering the reported annual loss of crops in Brazil and the mean proportion of crop losses related to pests, we estimate the value of natural control of native pests in Brazilian crops to be 23.6 billion dollars annually. To estimate the potential contribution of anurars to pest control we first assessed dietary information and quantified their potential to control insect populations.

Based on our sampling of anurans in Central Brazil, stomach content comprised up to 107 individual prey with an average number of six individuals (± 5.28 prey). The maximum total prey volume estimated for sampled anurans was 6,071 mm³. Formicidae was the most abundant prey, comprising 18% of the total number of prey, followed by Araneae, Hemiptera, and Diptera (11%). Formicidae alse had the largest contribution to total volume of ingested prey (17%), followed by Araneae (16%) and Hemiptera (15%) (Figure 1). Based on the dietary patterns of sampled assemblages and estimates of anuran activity, rate of digestion, and population size, we estimate that during an entire year, in a 100m² pond, the mean number and volume of prey ingested by an anuran assemblage would be 1,205,747 individual prey comprising 3,676 cm³. For a community in a pond with 500 m², these estimates would increase to 6,028,736 prey individuals and 18,381 cm³ (Table 1). Accordingly, we estimate the value of natural control of native pests attributable to anurans in Brazilian crops to be 1.18 billion dollars annually (Table S1).

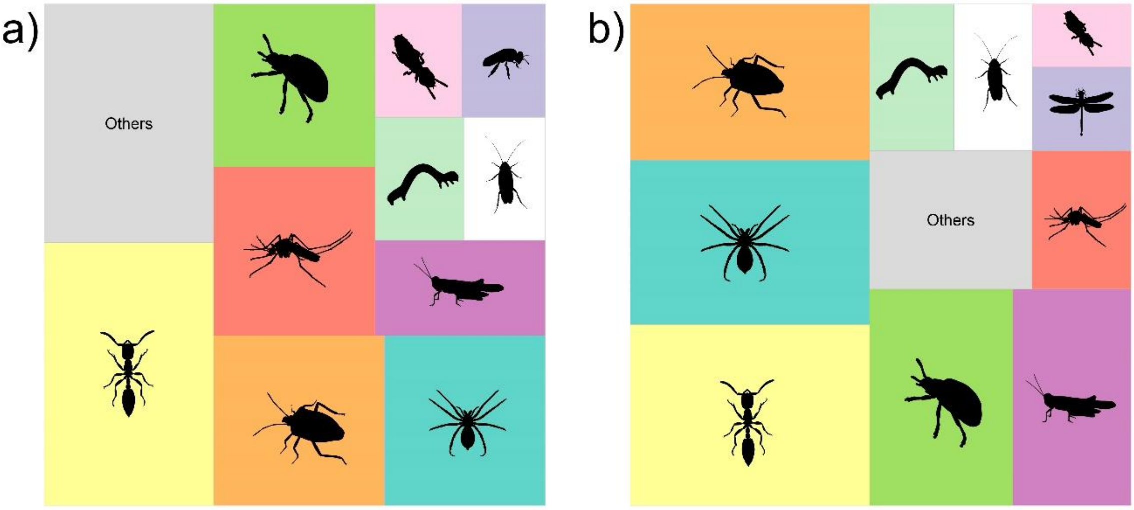

Figure 1: (a) Numeric and (b) volumetric proportion of invertebrates consumed by an anuran community during a year. Invertebrate silhouettes are from PhyloPic (2023).

Table 1: Number and volume (cm³) of consumed prey by amphibians annually in ponds of different sizes in the Atlantic Forest, Cerrado, Chaco, and Pantanal ecoregions.

Sites/Pond size	**Number of prey**		**Volume (cm³)**	
	500 m²	**100 m²**	**500 m²**	**100 m²**
Cerrado	3,738,650.00	747,730.00	21,463.51	4292.70
Chaco	4,109,824.00	821,965.00	10,976.93	2195.39
Atlantic Forest	10,608,673.00	2,121,735.00	23,634.28	4726.86
Pantanal	5,657,799.00	1,131,560.00	17,453.11	3490.62
Mean	6,028,736.50	1,205,747.50	18,381.96	3,676.39

Cerrado as a study case

The majority of ponds/lakes in the study region were located next to cropland (Figura 2 a–c) and at the edge of rivers (Figura 2c). Considering the distribution of ponds and lakes and the area they occupy, we estimate that anurans have the potential to prey on 291.614.700 invertebrates or 62,400,000 cm³ annually in this region. The minimum value of annually consumed prey in Central Brazil close to crops was 2.5 million of prey (or 160,000 cm³) by pixel (55 km of resolution), located mainly in the southeastern region, which contains a smaller density of ponds, whereas the maximum estimate sums up to 12.5 million inidividual prey annually (between 640,000 and 800,000 cm³), which are located in the central region and east region (Figure 2 a–c).

The estimate of annual soybean savings due to biological control in Cerrado is 155,538,168 dollars (Figure 3b). When soybean crops and ponds are overlaid, we conservatively estimated the potential savings attributable to anurans, assuming that less than 5% of the total biological control is performed by anurans alone, in 498,257 dollars per year (Figure 3 a, c)

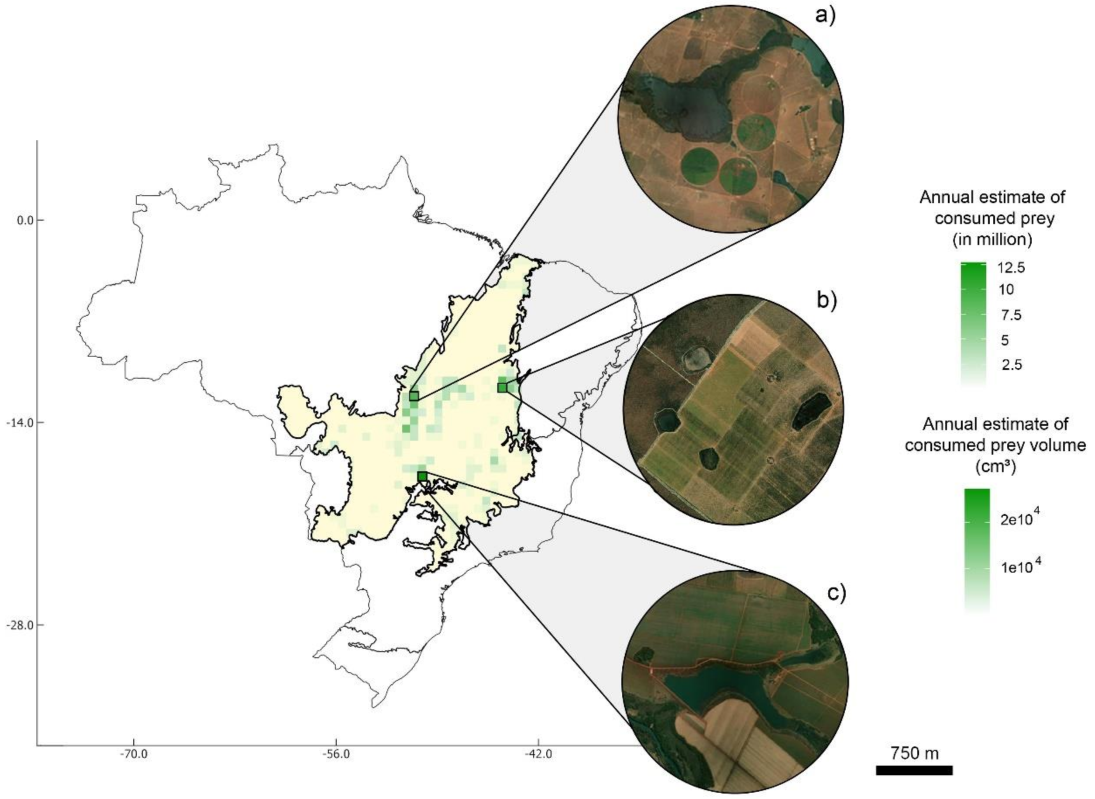

Figure 2: Annual estimate number and volume of consumed prey by anurans in the Cerrado ecoregion, Brazil. Each pixel corresponds to 3,000 km².

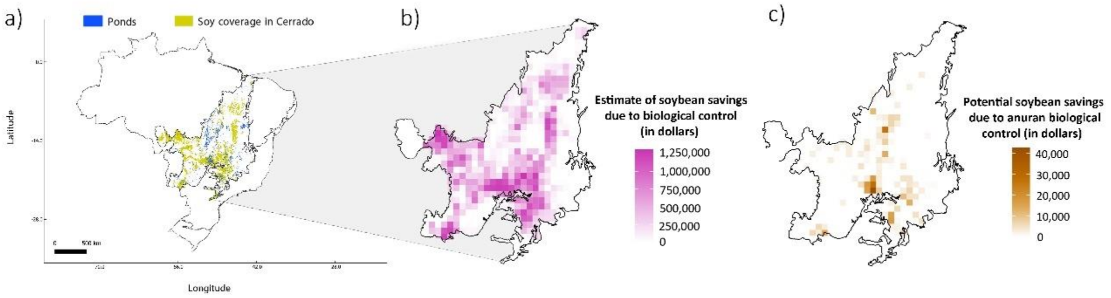

Figure 3: Estimate of soybean savings due to biological control in Cerrado, where: a) Ponds/lakes and soybean coverage in Cerrado, b) Annual estimate of soybean savings in Cerrado due to biological control, and c) Annual potential soybean savings attributable to anuran’ biological control in Cerrado. Each pixel corresponds to 3,000 km².

Discussion

Amongst the consumed prey by anurans, the majority of orders include crop pests and vector diseases, such as Formicidae, Hemiptera, and Diptera. Anurans contribute to the regulation of invertebrate populations consuming millions of individuals per year in a single pond. When restricting this to areas close to crops and potential crop pests, we conservatively estimate the value of natural control attributable to anurans to be more than $1.18 billion annually for all crops and nearly half a million dollars only for soybeans cultivated in Central Brazil.

The evidence of population control by anurans in the literature is anecdotal. Yet, considering our estimates that in a single pond anurans can eat more than a million individual prey in a year and that the majority of density esimates for invertebrates are below 100 ind/m² (Lavelle et al. 2022), it is reasonable to assume that anuran control invertebrate populations. Among the most consumed prey, Formicidae was the most abundant and comprised most of the volume of prey found in anuran stomachs. Previous studies showed that anurans eat ant genera that can impact crops (Gruber et al. 2022), such as leaf-cutting ants and fire ants (Diaz et al. 2020, Oliveira et al. 2023). However, their small size, proportionally lighter weight, and non-digestible parts (pers. observation.) may not contribute much biomass/energetic content compared to slightly larger and heavier spiders, larvae, or grasshoppers (Sage 1982), thus requiring a great number of individuals to cover anuran energetic demands. In this sense, ant-specialists anurans can eat several ants in a short time space, once some ant nests or ants trails are located at the ground level and once a trail is located they tend to pick up ants as they pass by. In this study, a single individual of the small-sized (21.81 mm) *Elachistocleis matogrosso* from Pantanal showed 86 ants in its stomach and one individual of medium-sized 35.44 mm) *Rhinella bergi* from Chaco was found with 104 ants in its stomach.

Hence, is rationale assume that an anuran population may regulate ant populations, once in general ants have a density of 303 ind/m² (Lavelle et al. 2022) and an ant colony in Tropical region may harbor ca. 1,000 individuals (Kaspari and Vargo 1995).

Hemipterans are known to cause diseases and impact yealds worldwide. In Latin America, kissing-bugs (Hemiptera: Reduviidae) are vectors of Chagas disease, which infects 6–7 million people worldwide (WHO 2023). They also figure as important pests in agriculture, for example, the rufous scale *Selenaspidus articulatus* is well known for its injury on *Citrus* spp. (also named as citrus pest), causing early ripening, stains, discoloration of fruits and loss of leaves. This activity causes fruits to be smaller, reducing the overall yield by some 30% (Oliveira et al. 2013). The whitefly *Bemisia tabaci* inflicts direct damage to vegetables by extracting sap from the phloem, weakening the plants and secreting a sweet substance (honeydew) that prompts the growth of saprophytic fungi (Oliveira et al. 2001). Apart from causing direct harm, this pest also serves as a vector for transmitting viruses that result in a variety of diseases. Crops such as soybeans, cotton, beans, and numerous leafy vegetables may experience losses ranging from 20% to 100% when under attack by the whitefly (Oliveira et al. 2013). Despite anurans frequently eat these orders in abundance (Ceron et al. 2019, Michelin et al. 2020), there is no information about the impact of this supression provided by anurans in these populations. For example, an individual of the cururu toad (*Rhinella diptycha*) presented 32 coleopterans in the stomach during the dry season in Chaco while the small foam-nesting frog (*Leptodactylus podicipinus*) had found with four hemipterans in its stomach in Cerrado, but the extent of these predation on pests population is unknow.

In addition to their potential to control the population of crop-pests, anurans can consume different species, especially mosquitoes, known to act as disease vectors.

Arboviral diseases, which include dengue, zika, and chikungunya virus, are mainly transmitted by *Aedes* (*Stegomyia*) *aegypti* mosquitoes (Magalhaes et al. 2020), malaria is transmitted by *Anopheles* mosquitoes (Carlos et al. 2019), and visceral leishmaniasis by phlebotomine sand fly (*Phlebotomus* and *Lutzomyia* genus) (Harhay et al. 2011). Many studies have demonstrated that anuran can reduce mosquito populations and stop the spread of vector-borne diseases such as malaria (e.g., Springborn et al. 2022). Tadpoles can compete and prey on mosquitoes larvae, and after metamorphosis, amphibians adults can prey upon a great number of mosquitoes (Peltzer and Lajmanovich 2002, Mokany and Shine 2003, Salinas et al. 2018). In this study, we noticed that many species preyed upon mosquitoes, mainly aquatic and semi-aquatic species. For example, in the diet of one individual of the small-sized (16.41 mm) *Lysapsus limellum* from Pantanal, we found 16 adult mosquitoes, that had been eaten in a single night. Similar observations were obtained Argentina where the majority of the fly species that compose the diet of this frog belong to the family Ephydridae, which causes human diseases (Peltzer and Lajmanovich 2002). However, whether these predation events do regulate mosquito populations is a question that warrants further research

Not all anurans are active all year round. Usually, anurans' activity is regulated by abiotic factors such as temperature, and rainfall in the tropics and neotropics (Prado et al. 2005), and aggregations to breed are common to occur during the wet and hot seasons, where breeding resources, such as water, are not a limitation factor (Duellman and Trueb 1986). In this sense, anuran communities show a nonstationary pattern in the species-environment relationship throughout the year, showing a turnover among species according to their responses to climate variables (Ceron et al. 2020a). During drier and colder months, anurans reduce their performance and may aestivate in semiarid environments, which can reduce the number/volume of consumed prey during this period (Wells 2007, Carvalho et al. 2010). Conversely, some species are specialized to be active during colder months (e.g., cold-adapted species) due to this higher thermal tolerance (Kiss et al. 2009), creating a gradient of activity among species along the year, which can maintain anuran services throughout the year, despite these fluctuations in abundance between seasons. Nonetheless, insect abundance shows a seasonal pattern in Brazil, with greater abundance in warm-rainy periods (Silva et al. 2011, Medeiros-Sousa et al. 2015), trending similar to the amphibians, which turns more abundantly in the rainy season (Duellman and Trueb 1986), resulting in a high temporal overlap both in larvae stages and adults.

The anuran dietary pattern upon crop pests and vector diseases seems complementary to that provided by bats and birds. This complementarity raises from the differences in quantity, activity shifts, foraging mode, and microhabitat use, which results in different diets. While insectivorous bats are strictly nocturnal, birds and anurans have both nocturnal and diurnal species (Duellman and Trueb 1986). Whereas bats and insectivorous birds usually catch and eat pests through aerial hawking next to the ground (Kunz et al. 2011), anurans can eat terrestrial and scansorial pests through opportunistic and or active searching (Toft 1981) in addition to control promoted by the ingestion and competition with aquatic larvae. Accordingly, the diet of most insectivorous bats consists of large quantities of lepidopterans (moths), coleopterans (beetles), dipterans (flies), and hemipterans (true bugs, cicadas) (Kunz et al. 2011), while insectivorous grassland birds usually fed on grasshoppers (Orthoptera), and tropical forest and farmland birds frequently consume beetles, ants, cockroaches (Blattodea), katydids (Orthoptera), caterpillars, and spiders (Nyffeler et al. 2018). In contrast, anurans can eat a wide array of prey conforming to their availability in the environment (Ceron et al. 2022), which includes ants, dipterans (mosquitoes), spiders, beetles, and hemipterans. In this sense, this complementarity can enhance the biological control of pests and disease vectors through a mix of predators that present singular characteristics but that can act together to control invertebrates populations.

Despite the long tradition of assessing frogs' dietary preferences (e.g., Duellman 1978), and more recently assessing the potential ecosystem services provided by amphibians (Civantos et al. 2012, Valencia-Aguilar et al. 2013, Hocking and Babbitt 2014), there is no information about the monetary value of them to pest control. We provide here a groundbreaking estimate suggesting that anuran amphibians contribute to pest control. The estimated value is comparable to the values attributable to the biological control of bats and beneficial insects (e.g., Losey and Vaughan 2006, Tuneu-Corral et al. 2023). For example, for cotton crops in Australia, USA, and Mexico, bats save on average $2.87 billion (741,000 – 22,9 billion) per year, for Macadamia crops in South Africa they save on average $2.45 million per year (Taylor et al. 2017), for rice paddies in Thailand ca. $1.21 million per year (Wanger et al. 2014) and for corn crops from USA and Brazil bats save on average $694 million annually (Tuneu-Corral et al. 2023). For native beneficial insects in the USA, Losey and Vaughan (2006) estimated that they contribute to savings of $4.49 billion per year among crops. However, economically quantifying the pest control services provided relies on assumptions regarding several unknown parameters. Regardless, our conservative approach allowed us to provide a baseline estimate for the economic contribution of amphibians to biological control.

Cerrado as a study case:

We estimate that Central Brazil affords efficient invertebrates biological control through its biodiversity in croplands, with savings turning around billions of dolars per year with anurans feeding on ca. 300 millions of invertebrates annually. This highly effective biological control done by biodiversity is essential to maintaining the health of ecosystems and thus yield production (e.g., Anjos et al. 2022, Shine et al. 2023). Even in this scenario of biological control, estimates of the losses caused by insect attacks on the Brazilian major crops vary between 2 and 43%, with 7.7% on average, despite the adoption of control measures (Oliveira et al. 2014). Without this biological control acting against pest crops, this annual loss may be 65% greater (Losey and Vaughan 2006), a relevant loss to mid/low-income countries.

The advance in land use modification and native vegetation degradation in Central Brazil, combined with climate change, which is projected to make this region hotter and drier in the future, are the main threats to the vital functions promoted by biodiversity (Grecchi et al. 2014, Rodrigues et al. 2022). In a cascading effect, these modifications will impact species mainly through habitat loss and water restriction, which can certainly impact the pest control provided by them, eventually resulting in an increase in crop losses due to pest outbreaks (Ceron et al. 2023). With the disruption of pest control services provided by amphibians and other organisms, the use of insecticides and levels of contamination might increase over time, which may result in higher rates of poisonings due to the growing use of pesticides in a future scenario if the pest control service breaks. In this sense, Cerrado conservation is essential to maintain its vital functions, which boosts agricultural productivity through water availability and its natural pest management provided by animals such as amphibians.

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