

SIA-BRA: A database of animal stable carbon and nitrogen isotope ratios of Brazil

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Abstract

Motivation: SIA-BRA is a data set that compiles stable carbon (C) and nitrogen (N) isotope ratios of terrestrial and aquatic animals sampled in Brazilian biomes and coastal marine areas. Stable isotope ratios are helpful in animal ecology for several reasons; for instance, they can be used to investigate trophic niches, energy sources (diet tracing) and to track migration patterns. The Neotropics are considered one of the most undersampled regions of the world. Given that Brazil is a continental country where most of the dietary ecology of animal species is under-assessed, we believe that the SIA-BRA can provide important complementary information to address this gap in the literature. Additionally, the SIA-BRA data set allows future investigations to address many questions concerning diet tracing, habitat use, food webs, foraging ecology, physiological aspects and effects of phylogeny on dietary ecology.

Main type of variable investigated: Carbon and nitrogen stable isotope ratios for terrestrial and aquatic animals.

Spatial location and grain: The SIA-BRA included animal tissues sampled in 964 sites in the main Brazilian biomes and coastal marine areas.

Time period: The data represent information published and/or sampled from 1984 to 2021.

Major taxa studied and measurement level: The SIA-BRA contains isotopic data of c. 21,804 non-captive wildlife specimens, excluding livestock production or laboratory experiments. They were 13,881 vertebrates and 7,923 invertebrates. They were divided into the following habitats: terrestrial (30% of the total), freshwater (27%), oceanic (40%) and estuarine (4%). There were 11 phyla, with a clear dominance of Chordata (64%) and Arthropoda (29%), 36 classes, 154 orders, 473 families, 894 genera and 1,157 species.

Software format: Data are supplied as a comma-delimited text file (.csv).

KEYWORDS

¹³C, ¹⁵N, diet, macroecology, Neotropical region, wildlife

1 | INTRODUCTION

Animals play a key role in transferring organic matter and energy from primary producers through the food webs (Lesser et al., 2020).

They are involved in regulating major processes, such as carbon (C) sequestration, distribution of invasive species, biogeochemical cycles and disease dynamics (Estes et al., 2011). Therefore, an understanding of the functional roles of animal species and communities

is essential for the ecological functioning in any ecosystem (Sinclair et al., 2003).

Brazil is a continental and hyperdiverse country with 120,176 verified animal species (90% invertebrates and 10% vertebrates) (Boeger et al., 2021). Almost 4,400 bonefish, 3,100 birds, 1,000 amphibians and >700 species of mammals and reptiles have been described in the territory (Boeger et al., 2021; de Piacentini et al., 2015). Therefore, it is a daunting task to evaluate the trophic ecology of the diverse fauna using the traditional methods in such a large area. In this context, using several investigatory techniques and information available in widely accessible data sets could provide a clearer perspective of the extensive trophic ecology of Brazil.

In recent decades, stable C and nitrogen (N) isotope ratios have been used extensively to unveil animal trophic ecology (Cucherousset & Villéger, 2015; Inger & Bearhop, 2008; Parnell et al., 2013). The proportion of C_3/C_4 plants in the diet is reflected in the stable C isotope composition of consumers (Inger & Bearhop, 2008), used to differentiate resources in aquatic ecosystems (March & Pringle, 2003), aquatic–terrestrial energy transfers (Radermacher et al., 2020) and even to differentiate plant- and detritus-based trophic chains (Potapov et al., 2019). Brazil has contrasting signatures, in which wild C_3 vegetation coexists with native and invasive C_4 plants (Souza Jr et al., 2020). Complementary, stable N isotope ratios are widely used in diet-tracing studies, providing information on trophic levels within food chains (Hobson & Clark, 1992; Layman et al., 2012; McCann, 2007; Newsome et al., 2010; Vogel, 1978). Also, stable N isotope ratios indicate changes in environmental factors that influence the whole food web, such as pollution by nitrate and ammonium, allowing the evaluation of animal ecology (Prado et al., 2020).

Here, we present the SIA-BRA data set, a compilation of stable C and N isotope ratios of terrestrial and aquatic animals sampled across the Brazilian territory. Our exploratory question is how much animal geographical location, habitats, dietary guilds and types of tissues account for the variance of stable C and N isotope ratios.

We believe that the SIA-BRA will contribute to a better understanding of the trophic ecology of Brazilian species. Additionally, the SIA-BRA will allow future studies to address many questions concerning diet tracing, habitat use, food webs, foraging ecology and effects of phylogeny on dietary ecology.

2 | METHODS

2.1 | Data sources and compilation

The SIA-BRA data set includes peer-reviewed articles and doctoral theses published in English, Portuguese and Spanish, and unpublished data from the Laboratory of Isotope Ecology (LEI) of the University of São Paulo. To achieve our goals, we essentially used academic search engines, such as Web of Science, Scopus, SciELO and Google Scholar, in addition to thesis repositories of Brazilian universities based on the following keyword combinations (also in Portuguese): “isotope Brazil”, “13 carbon Brazil”, “15 nitrogen Brazil”, “isotope animal Brazil” and

“stable isotope animal Brazil”. We limited our search to publications containing original data about non-captive wild specimens, excluding livestock production and laboratory experiments, where animals receive food supplements. To avoid duplicates, we compiled data only from original research papers rather than those found in meta-analysis studies, except when data were provided. We extracted data from tables and text when available, together with WEBPLOTDIGITIZER software (v.4.2; Rohatgi, 2012) to convert graphical into numerical data. The data set encompasses data collected from 1984 to 2021, and the search process was updated until July 2021. We accessed 196 data sources between peer-reviewed articles, academic theses and unpublished data provided by co-authors of this study (<https://doi.org/10.5281/zenodo.4609306>).

2.2 | Quality assurance and quality control

We compiled a database of stable C and N isotope ratios from animal tissues sampled exclusively from the Brazilian territory, reporting them without any trophic discrimination factor. As part of quality assurance, each data source was checked carefully for the selected parameters. Outliers detected by plots in R, using “ggplot2” (Wickham, 2016), were double-checked in the original source and maintained in the data set. Therefore, users can adopt alternative methods for outlier detection when handling the SIA-BRA data set for specific purposes.

Species names were checked against the “Global Biodiversity Information Facility” using the “rgbif” R package (Chamberlain et al., 2020) to combine infraspecific taxa with their parent species and to remove duplicates. We estimated that 80% of the entries in the data set have species taxonomic classification, most of them vertebrates, whereas invertebrates were identified mostly to order or family level.

2.3 | Data structure

The SIA-BRA is presented in a single file containing a .csv spreadsheet with several columns containing bibliographical information, latitude and longitude of sampling, climatic variables and the taxonomy related to the $\delta^{13}C$ and the $\delta^{15}N$ values of animal tissues plus additional information (the laboratory where the isotopic analysis was conducted and whether lipids or minerals were extracted from the samples; Table 1).

There are three types of data sources: (a) published papers are characterized by the name of the first author, year of publication, and a digital object identifier (DOI) link; (b) for academic thesis, for which, a DOI is not available in some cases, other links were provided instead; and (c) “unpublished” data, which refers to data not yet published in peer-reviewed journals (<https://doi.org/10.5281/zenodo.4609306>).

Sampling sites were identified by their geographical coordinates converted to decimal degrees using the DPI tool of The Brazilian

National Institute of Space Research (<http://www.dpi.inpe.br/calcula>) and Google Earth (v.9.143; Google). Climatic variables [mean annual temperature (MAT) and mean annual precipitation (MAP)] were obtained from the WorldClim v.2 database (from 1970 to 2000, with c. 21 km² spatial resolution; Fick & Hijmans, 2017) using the "raster" R package (Hijmans et al., 2020). The geographical coordinates of the sampling site were also used to classify them into the six major Brazilian biomes (Amazon, Atlantic Forest, Caatinga, Cerrado, Pampa and Pantanal) and in the coastal marine system according to the Brazilian Institute of Geography and Statistics (IBGE, 2012) (Figure 1). Sampling sites with unknown geographical coordinates were maintained in the data set, identified as "several sites" if sampling occurred in many places or as "blank" if the locations of the sites were not mentioned clearly in the original research papers. We acknowledge that the uncertainty of geographical coordinates could be inappropriate for some investigative purposes, but given that the aim of the SIA-BRA data set is to be a source of isotopic data for macroecological analysis, we believe that those data

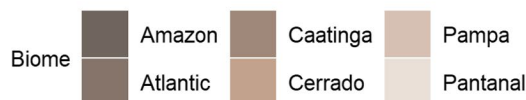
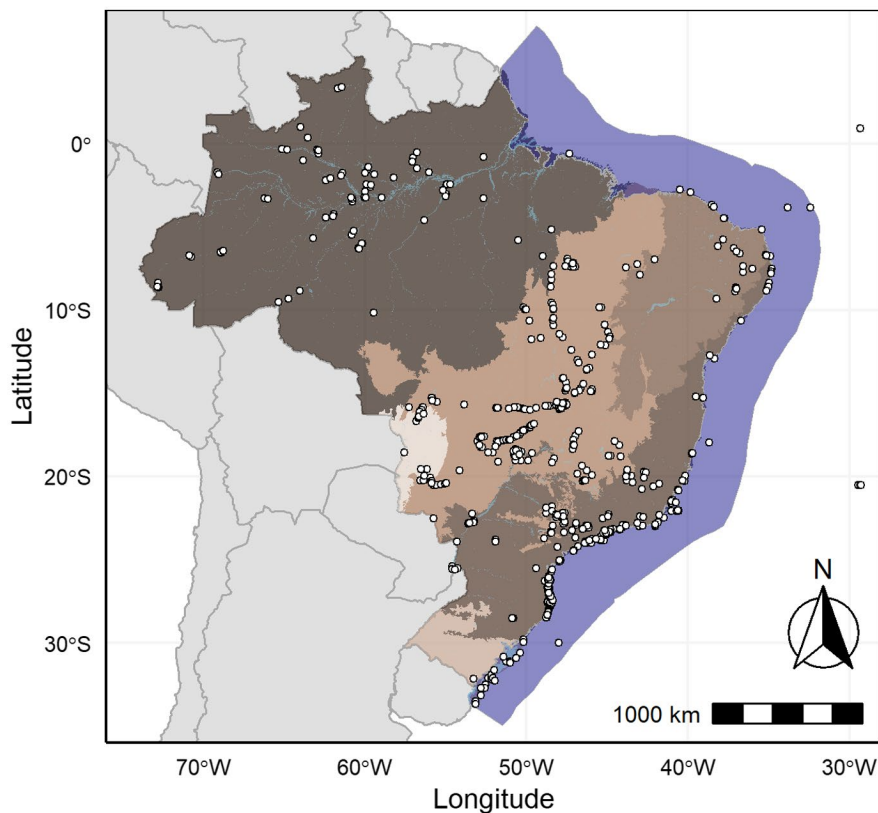
are still useful. To minimize this lack of information, we identified the administrative region of the site (i.e., state) wherever possible. To facilitate future analysis, we also grouped animals by their living environments into terrestrial, freshwater, estuarine and oceanic, based on the information provided by the original research papers and the sampling site.

The data set also contains the analysed tissue of each organism, classified in larger groups with similar biochemical composition and isotopic turnover rates: keratin (including claw, hair, feather, reptile and insect carapace, rattle, whisker, scute, fin, skin/epidermis and wing membrane), bone (including bone, teeth and shell), muscle (dorsal and muscle of unidentified origin), organ (including liver, heart, stomach, intestine, gill, gonad, hepatopancreas, kidney, venom and egg), blood (including plasma, serum, red blood cells and total blood), soft tissue (column, foot and mantle tissues) and whole animal (including the digestive system or not). In some cases, more than one tissue type was sampled per specimen, allowing future comparisons of stable isotopic ratios across different tissue types. Some studies reported

Heading	Description	Type
Author	First author of the publication	Character
Title	Title of the study	Character
Year	Year of publication	Numerical
DOI	Digital object identifier	Character
Local	Sampling site	Character
Biome	Sampling biome	Character
Latitude	Geographical coordinate (decimal degrees)	Numerical
Longitude	Geographical coordinate (decimal degrees)	Numerical
MAT	Mean annual temperature (in degrees Celsius) from WorldClim v.2	Numerical
MAP	Mean annual precipitation (in millimetres) from WorldClim v.2	Numerical
Ecosystem	Aquatic, terrestrial	Character
Habitat	Estuarine, freshwater, oceanic, terrestrial	Character
Sampling	Sampling years	Numeric
Group	Invertebrate, vertebrate	Character
Phylum	Taxonomic information	Character
Class	Taxonomic information	Character
Order	Taxonomic information	Character
Family	Taxonomic information	Character
Genus	Taxonomic information	Character
Species	Taxonomic information	Character
Diet	Dietary guild (carnivore, herbivore or omnivore)	Character
Samples	Number of observations	Numerical
Raw tissue	Types of animal tissues	Character
Tissue	Merged types of animal tissues	Character
Laboratory	Laboratory that processed the samples	Character
Extraction	Lipid or mineral extraction	Character
d ¹³ C	Stable C isotopic ratio (per mil), δ ¹³ C	Numerical
d ¹⁵ N	Stable N isotopic ratio (per mil), δ ¹⁵ N	Numerical

TABLE 1 Summary information found in the SIA-BRA data set

FIGURE 1 Map of Brazil, with boundaries of major biomes (brown) and the main rivers (light blue), showing the sampling sites (white dots). Sites outside the Brazilian coastal marine zone (dark blue) are islands that compose the Brazilian territory (Saint Peter and Saint Paul Archipelago and Trindade and Martim Vaz Archipelago)



mean isotopic ratios only among several specimens; in these cases, the mean values are reported together with the number of samples.

Information about classification of dietary guilds was retrieved using the Google Scholar search engine following keyword combinations (also in Portuguese) of the “species name” plus “diet”, “trophic guild”, “feed on” and “foraging items”. Animals that feed only on producers (plants, algae or phytoplankton) were classified as herbivores (HER); animals that feed on animals (invertebrates or vertebrates) and producers (in different proportions) were classified as omnivores (OMN), and the ones that feed only on animals were carnivores (CAR). In addition, we elaborated a baseline for each main habitat (i.e., terrestrial, freshwater and marine) gathering the isotopic values of plants, periphyton, detritus, algae and phytoplankton, presented in the same original studies used for the animal data (Table 2).

2.4 | Data availability and access

The SIA-BRA data set is an active project including updates and corrections. The current version is published via a public repository (<https://doi.org/10.5281/zenodo.4609306>). The data set is released as five files, namely: (a) the complete data set (i.e. SIA-BRA_1.0) itself, supplied as a comma-separated value (.csv) file; (b) a .csv file describing the species with specimens sampled for more than one

TABLE 2 Average $\delta^{15}\text{N}$ values of primary producers, with confidence intervals (CI), and number of samples (count) in freshwater, marine and terrestrial habitats

Habitat	Average	-95% CI	+95% CI	Count
Freshwater	4.1	3.5	4.6	75
Marine	6.6	-6.2	7.0	190
Terrestrial	3.6	2.9	4.3	26

tissue (SIA-BRA_specimens); (c) a data set of the baseline elements (SIA-BRA_baseline); (d) a .csv file describing header information of column found in the SIA-BRA (Table 1; SIA-BRA_metadata); and (e) an R script (SIA-BRA_script) containing the R codes used for performing the statistical and graphical analysis. Data should be gathered in the recent version of the database in this permanent repository. Contributions to expand the SIA-BRA database are welcome and desirable, mostly for those regions where data are lacking.

2.5 | Description of the data

The SIA-BRA contains 21,221 and 20,936 observations of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of sampled animals, respectively. They encompass 21,804 animal entries, including 13,881 vertebrates and 7,923 invertebrates.

There are 11 phyla, with a clear dominance of Chordata (63%) and Arthropoda (30%), 36 classes, 154 orders, 473 families, 894 genera and 1,157 species. Our first finding is that >99% of the Brazilian fauna species still lack isotope information.

Approximately 44% of the data in the SIA-BRA came from coastal marine systems (oceanic plus estuarine) and 56% from continental areas (terrestrial plus freshwater). In continental areas, C and N isotope composition is reported for animals living in the Cerrado (23%), in the Atlantic Forest (15%) and in the Amazon biome (11%); values for animals from the other biomes represent <5% of all data. Observations are still very scarce in the Pampa, Caatinga and Pantanal biomes and in many areas of all the Brazilian biomes (Figure 1).

The baseline C and N values compromise 3%, 15% and 14% of terrestrial, freshwater and marine habitats, respectively, of the sites of SIA-BRA data set from the same original studies used for the animal data (Table 2, repository). It is important to notice that these values occurred in <9% of the studies from the data set.

2.6 | Preliminary statistical tests

We explored the SIA-BRA data set initially by plotting histograms of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, categorizing organisms as vertebrates and invertebrates, then as terrestrial, freshwater and marine organisms, which

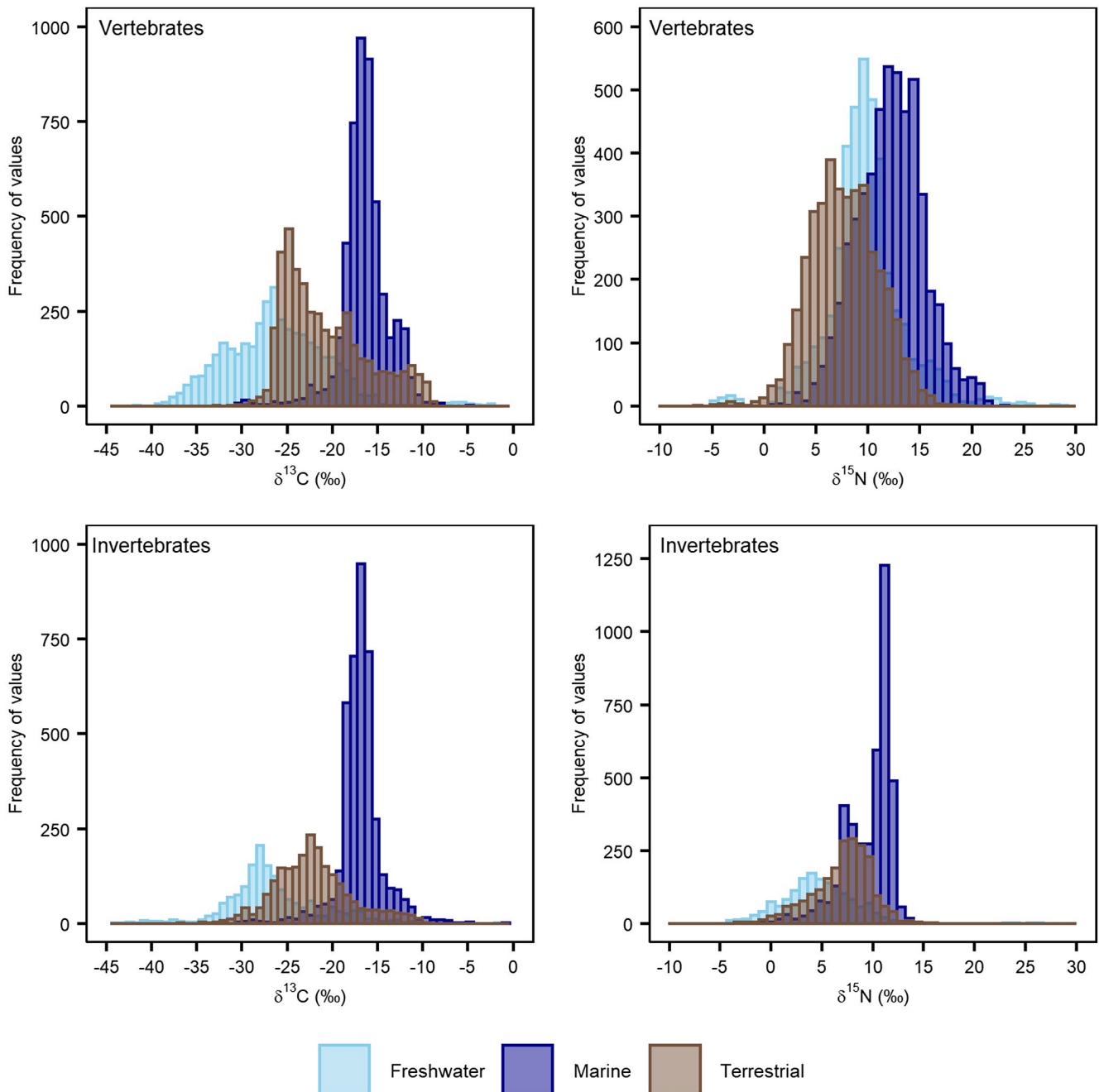


FIGURE 2 Histogram of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of freshwater (light blue bars), marine (dark blue bars) and terrestrial (brown bars) organisms

TABLE 3 Average $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, with confidence intervals (CI), and number of samples (count) in freshwater, marine and terrestrial animals

Isotope	Group	Habitat	Average	-95% CI	+95% CI	Count
$\delta^{13}\text{C}$	Invertebrates	Freshwater	-26.5	-26.8	-26.3	1614
		Marine	-16.9	-17.0	-16.8	4130
		Terrestrial	-22.1	-22.2	-21.9	2179
	Vertebrates	Freshwater	-26.5	-26.4	-26.0	4186
		Marine	-16.4	-16.5	-16.3	5418
		Terrestrial	-20.7	-20.8	-20.6	4277
$\delta^{15}\text{N}$	Invertebrates	Freshwater	4.8	4.6	5.0	1614
		Marine	9.6	9.5	9.7	4130
		Terrestrial	7.0	6.9	7.1	2179
	Vertebrates	Freshwater	9.8	9.7	9.9	4186
		Marine	12.2	12.1	12.3	5418
		Terrestrial	7.7	7.6	7.8	4277

include estuarine and oceanic organisms (Figure 2). Variance partitioning analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ for vertebrate and invertebrate organisms was conducted (Asner & Martin, 2016; Fyllas et al., 2009) using a multi-level generalized linear mixed-effect model (GLMM). The model parameters were estimated by a residual maximum likelihood method (REML), considering random factors in a nested design as: biomes, habitats (freshwater, marine and terrestrial) and paper, representing the sampling sites, using the combination of the name of the first author and date of publication; followed by tissue type (blood, collagen, keratin, muscle, organs and whole body) and dietary guild (herbivore, omnivore and carnivore). Dietary guilds were assumed only for vertebrates, because of the low taxonomic resolution of invertebrates, making the classification not reliable.

To perform this analysis, we first tested the normality of the residues, using the R package "fitdistrplus" (Delignette-Muller & Dutang, 2015). The *Imer4* and the *ImerTest* R packages were used to run the GLMM (Kuznetsova et al., 2017). To estimate the pseudo- R^2 for GLMM, the R package "MuMIn" was used (Bartoń, 2020). This package estimated the variance explained by the fixed effect (marginal R^2_{GLMM}) and the variance explained by the whole model, the sum of fixed and random variables (conditional R^2_{GLMM} ; Nakagawa et al., 2017). The R codes of the models can be found in the permanent repository (<https://doi.org/10.5281/zenodo.4609306>).

3 | PRELIMINARY RESULTS AND DISCUSSION

Continental organisms had more negative $\delta^{13}\text{C}$ values than marine ones. Freshwater animals had lower $\delta^{13}\text{C}$ values than terrestrial ones, for vertebrates and invertebrates (Figure 2). For continental organisms, those values reflect higher assimilation of C_3 primary producers in the former and a higher assimilation of C_4 plants in the latter (Table 3), given that grasses are naturally abundant in drier biomes of the country, such as the Cerrado, and in human-modified landscapes, dominated by forage C_4 grasses, maize and sugarcane (Boesing et al., 2021; Magioli et al., 2019). The less negative $\delta^{13}\text{C}$ of

marine animals than of continental animals reflects the assimilation by primary producers of ^{13}C -enriched dissolved inorganic C (Laws et al., 1995), rendering, in mid-latitudes, $\delta^{13}\text{C}$ phytoplankton values from -23 to -16‰ (Magozzi et al., 2017).

In general, the $\delta^{15}\text{N}$ of invertebrates was lower than the $\delta^{15}\text{N}$ of vertebrates. Although the mean values were not distinct (Table 3), the values shown in the histogram indicate this pattern (Figure 2). The ^{15}N enrichment that occurs along food chains, with vertebrates occupying higher levels than invertebrates, is probably the cause of this difference. Among invertebrates, marine organisms also had the highest $\delta^{15}\text{N}$ values, but the freshwater invertebrate values were lower than the terrestrial ones, contrary to the pattern for vertebrates. This difference is probably attributable to the higher $\delta^{15}\text{N}$ values observed in marine relative to freshwater and terrestrial primary producers (Table 2). Additionally, marine food chains tend to be longer than terrestrial and freshwater chains (Vander Zanden & Fetzner, 2007), further increasing the $\delta^{15}\text{N}$ values of consumers.

The random factors considered in the model explained most of the variance observed in the isotopic composition of animals (Figure 3). The pseudo- R^2 values of the GLMMs were 76% for $\delta^{13}\text{C}$ of both vertebrates and invertebrates, and 82% and 78% for $\delta^{15}\text{N}$ of vertebrates and invertebrates, respectively. Most of the variance was explained by the sampling site, the habitat and the biome, whereas only a small part of the variance was explained by tissues and dietary guilds (Figure 3b-d). Therefore, the primary sources of variation in the isotopic composition of animals were those linked to local characteristics, the habitat and the biome at the regional scale, and much less to the physiological factors and dietary guild of the animal. This emphasizes a clear need to calibrate isotopic values for isotopic baselines in trophic analyses. Our data show <9% of the sites with information on the isotopic baseline. This lack of information highlights that more effort is needed to gather isotopic values for producers in the sampling sites where animals are studied and in other sites. Also, a more detailed taxonomic identification of those producers and the animals in the trophic web is fundamental to subsidize future studies and models.

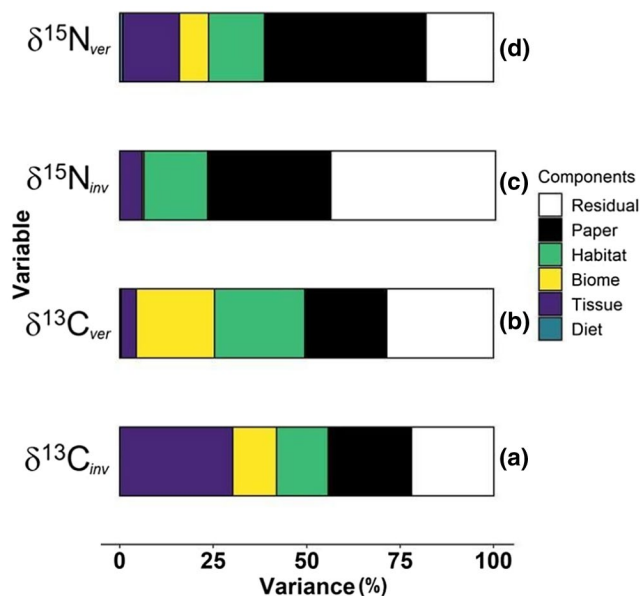


FIGURE 3 Variance partitioning of: (a) $\delta^{13}\text{C}$ of invertebrates, (b) $\delta^{13}\text{C}$ of vertebrates, (c) $\delta^{15}\text{N}$ of invertebrates, and (d) $\delta^{15}\text{N}$ of vertebrates. The key refers to components of the variance (random factors of the model). The estimate of the component for “Diet” was not included for invertebrates because dietary guild is not available for this group of animals. This variance component represents only a small proportion of the variance for vertebrates and is shown in the left side of the bars (a) and (c). The component for “Biome” was very close to zero for $\delta^{15}\text{N}$ of invertebrates; therefore, it is not shown in panel (c)

Overall, the SIA-BRA data set shows that stable isotopes have been used in animal biological studies in Brazil since the first publication in 1986 by the Laboratory of Isotope Ecology at the University of São Paulo, Brazil. Isotopic values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are available for almost 1% of Brazilian fauna spread across the Brazilian territory, and even within large areas, yet there is little isotopic information for most species.

SIA-BRA facilitates future studies addressing diet tracing, habitat use, food webs, foraging ecology, effects of phylogeny on dietary ecology, and physiological studies on Brazilian wildlife. This data set increases the availability of isotopic data for future studies with wildlife ecology in Brazil and acts as a reference of studies that were developed using this promising tool. Additionally, the SIA-BRA could work as a referential data set to study future changes in animal dietary ecology caused by rapid and intense changes in land use and climate throughout the country. Finally, we hope that the SIA-BRA could inspire similar initiatives in other parts of the world, with the hope that we might have a world-wide isotopic data set on all animals.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

L.A.M. and T.R.D.R. originally formulated the ideas presented in this paper. T.R.D.R., F.G.A., J.L.S., M.G.M., A.S.V., T.R.A., A.L.B., F.J.V.C.,

M.A.F., T.B.K., C.K., N.R.F.L., R.A.M.L., V.T.P., B.S.R., J.F.R., A.S.J., M.T.F., A.F., T.S.M., A.L.P., L.M.S.A., M.B.A., E.S.F.M., E.B., D.F.C., R.A.C., M.J.C., G.B.N., A.C.B.O. C.E.R., M.N.F.S., J.A.S.Z., L.M.V., M.Z.M., P.B.C. and L.A.M. provided the data for the empirical studies presented. T.R.D.R., F.G.A., A.A.F., M.G.A., S.S.F.C., R.F.A., E.B.P., C.P.S., J.L.S., C.F.C., T.F.G., M.G.M. and V.G. gathered data from published papers and theses. L.A.M., T.R.D.R., E.M. and P.D.N. were in charge of data analysis. L.A.M. wrote the first draft of the manuscript, and all authors contributed extensively to preparation and critical revision of the intellectual content of the final manuscript. All authors approved the final version to be published and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA AVAILABILITY STATEMENT

The authors confirm that the entire SIA-BRA data set and supplementary materials supporting the findings of this study are available at <https://doi.org/10.5281/zenodo.4609306>.

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BIOSKETCH

The work presented in this manuscript is the product of a research network devoted to using stable isotopes in animal ecology. This group investigates how Brazilian wildlife consume natural resources and respond to intensification of land use across Brazilian biomes. The working group is led by **Luiz Antonio Martinelli** of the University of São Paulo.

SUPPORTING INFORMATION

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