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LETTER

American manatees adjust their diet composition and trophic niche breadth across different coastal regions

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Scientific Significance Statement

Understanding the trophic ecology of endangered organisms is a key prerequisite for their conservation, particularly for species displaying great variability in foraging strategies. American manatees along the Brazilian coast inhabit a range of environments, though their regional dietary differences remain poorly characterized. Stable isotope analysis indicates that individuals from the Dry-Northeastern coast predominantly utilize marine areas and feed almost exclusively on seagrasses. Analysis of Northern coast manatees yielded results consistent with feeding in low-salinity habitats where seagrass was unavailable. Conversely, manatees from the Humid-Northeastern coast had the broadest trophic niche among the regions, with macroalgae representing an important dietary component. These findings are crucial for identifying critical habitats and guiding regional rehabilitation, release, and management strategies.

Abstract

Marine mammals can exhibit high plasticity in foraging strategies, but how such plasticity is driven by environmental conditions is poorly understood. The American manatee (*Trichechus manatus*), a large, endangered herbivore, inhabits marine, estuarine, and freshwater environments. To better understand their resource use, we

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analyzed dietary differences across three large Brazilian regions—the Northern Coast (NC), Dry-Northeastern Coast (Dry-NEC), and Humid-Northeastern Coast (Humid-NEC). The δ^{13}C and δ^{15}N values of manatee tissues increased from the NC to the Northeastern Coast. Stable isotope mixing models revealed that manatees from the Dry-NEC feed almost exclusively on seagrasses, while those from the NC rely predominantly on saltmarsh vegetation. In the Humid-NEC, manatees had a notable contribution from macroalgae, and exhibited the greatest dietary and habitat use diversity among the regions. These spatial patterns advance our understanding of large-scale habitat use, guiding the establishment of marine protected areas to safeguard manatees and their habitats.

Marine mammals can exhibit high variability and plasticity in foraging strategies across populations, life stages, sexes, and individuals (Heithaus et al. 2009). However, the extent to which local factors such as intraspecific competition and environmental conditions influence these strategies remains poorly understood. This knowledge gap is particularly critical for the American manatee (*Trichechus manatus*), a generalist herbivore that is currently listed as "Vulnerable" by the International Union for Conservation of Nature and Natural Resources (Deutsch and Morales-Vela 2024) and as "Endangered" in Brazil (Ministério do Meio Ambiente 2022).

Manatees use a wide range of habitats and provide important ecosystem services. As large-bodied herbivores, they act as nutrient recyclers by consuming aquatic vegetation and redistributing nutrients through feces and urine, thereby enhancing nutrient availability (Reynolds et al. 2008; Castelblanco-Martínez et al. 2012). Through grazing, manatees regulate macrophyte biomass, productivity, and species composition (Reynolds et al. 2008; Wirsing et al. 2022), helping maintain the structure and functioning of habitats that support high biodiversity and provide food, shelter, and nursery areas for other aquatic organisms.

Because these ecosystem services are directly mediated by feeding behavior, spatial variation in manatee diet has important implications for habitat functioning and ecosystem processes. In this context, pronounced regional differences in diet have been reported, with some populations feeding exclusively on freshwater vegetation, while others rely primarily on estuarine or marine resources (Reich and Worthy 2006; Alves-Stanley et al. 2010; MacAvoy et al. 2015; Normande et al. 2016; Santos et al. 2022). Throughout much of its geographic distribution, the species feeds mainly on seagrass meadows, particularly *Halodule* spp. and *Halophila* spp., as well as on macroalgae (Lima 1997; Paludo 1997; Borges et al. 2008). Studies in Florida and the Mexican Caribbean report a consistent preference for seagrasses even when alternative resources are available (Provancha and Hall 1991; Alves-Stanley et al. 2010; Garcés-Cuartas et al. 2025), indicating selective feeding and potential seasonal variation in diet according to resource availability (Allen et al. 2022).

Despite these findings, patterns of resource use across South American regions remain poorly understood. In Brazil, the American manatee is distributed across three major coastal regions: the Northern Coast (NC), the Dry Northeastern Coast (Dry-NEC), and the Humid Northeastern Coast (Humid-NEC). The NC is a mangrove-dominated region characterized by intense freshwater discharge and the absence of seagrass beds, where shoots and leaves of mangrove species (*Rhizophora mangle* and *Laguncularia racemosa*), as well as saltmarsh plants, appear to be important dietary components (Best 1981; Lins et al. 2014; Attademo et al. 2022). The Humid-NEC, in turn, comprises a high diversity of rivers, estuaries, and coastal habitats, including several marine protected areas, such as Costa dos Corais and the Mamanguape River Estuary Environmental Protection Areas. In contrast, the Dry-NEC is marked by the presence of seagrass and macroalgal beds, reduced freshwater input, and hypersaline estuaries, in addition to habitat scarcity and degradation that have reduced overall habitat suitability for manatees (Deeks et al. 2024a, 2024b).

Studies on the diet of the American manatee along the Brazilian coast have relied primarily on direct field observations (Paludo and Langguth 2002) and analyses of stomach contents (Borges et al. 2008); however, sample availability has largely been opportunistic, resulting in small sample sizes due to the rarity of stranded adult individuals. In this context, stable isotope analysis provides a valuable complementary tool, allowing the use of previously collected materials such as hard tissues and enabling broader ecological inferences. A key premise of stable isotope analysis is that the isotopic composition of consumer tissues reflects that of the assimilated diet (Newsome et al. 2010). This premise enables the application of isotopic mixing models to identify the main assimilated resources and to quantify isotopic niche breadth, thereby evaluating patterns of dietary specialization.

Given ongoing habitat loss and intense human pressure on ecosystems used by manatees, the analysis of carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopes is crucial for better understanding their trophic ecology and plasticity (Nielsen et al. 2018), thereby supporting more effective conservation planning. Specifically, we aimed to: (i) determine whether there is a latitudinal or regional gradient in diet and isotopic values; (ii) estimate the relative contribution of plant resources for each region; and (iii) compare isotopic niche breadth among regions. We predicted that manatees in regions lacking preserved estuarine and riverine habitats would rely more heavily on marine resources and exhibit reduced dietary diversity, whereas those inhabiting regions with heterogeneous habitat types would have greater dietary diversity and wider trophic niches.

Methods

Study region

We compared the trophic ecology of manatees across three distinct regions, classified according to Muehe (2010), which together cover more than 2500 km of the Brazilian coast (Table 1; Fig. 1A).

Sample collection and processing

Samples from American manatees were collected between 1989 and 2018 from deceased individuals found stranded on the shore, entangled in fishing nets, or that died within 3 months of being admitted to rehabilitation (Carvalho et al. 2025). We used both tooth and bone samples since previous analysis showed no differences in δ^{13}C and δ^{15}N values between these tissues (Ciotti et al. 2014).

Tooth and bone samples were brushed with distilled water to remove residual tissue and debris. Teeth were sectioned longitudinally using a low-speed diamond saw, and rinsed with distilled water. Samples were air-dried at room temperature for 24 h, after which dentin was extracted using a drill. The resulting powder was acidified with 30% hydrochloric acid (HCl) to remove inorganic carbon. Although acidification may slightly affect δ^{15}N values, HCl acidification by nebulization results in smaller and less variable changes than direct acid addition (Carrasco et al. 2018). The powdered dentin was oven-dried at 60°C for 2 h, and approximately 1 mg was encapsulated in tin capsules for stable isotope analysis.

Between 2011 and 2013, samples of manatee food resources were collected from high-occurrence manatee areas across the study regions (Fig. 1A). A minimum of three samples were collected for each species within each resource group present at each location. Macroalgae, seagrasses, and saltmarsh plants were collected in their entirety, while only the leaves were collected from mangroves. For the mixing models of the NC, data on macroalgae from Carvalho et al. (2022) were incorporated. Despite representing a relatively short time series when compared to the temporal window captured by tooth samples, the plant isotope values are consistent with the most recent values reported in the literature (Claudino et al. 2015; Bastos et al. 2022). First, we rinsed each specimen with distilled water to remove impurities and epiphytes. We then dried the samples in an oven at 60°C for 48 h. Once dried, we ground the plant material into a fine powder using a pestle and mortar and stored between 2.5 and 3 mg of the powdered material in tin capsules for stable isotope analysis.

Stable isotope analysis

We conducted isotopic analyses at the Center for Stable Isotopes at the University of New Mexico and Stable Isotope Core Laboratory, Washington State University. The Center for Stable Isotopes at the University of New Mexico uses a Costech 4010 elemental analyzer (Costech) coupled to a Thermo Scientific Delta V (Thermo Scientific) isotope ratio mass spectrometer; and the Stable Isotope Core Laboratory, Washington State University uses the same elemental analyzer connected to a continuous-flow isotope ratio mass spectrometer (Delta PlusXP, Thermofinnigan). Methodological details of the inter-laboratory comparisons and the correction equation are available in the Supporting Information.

We expressed the carbon (δ^{13}C) and nitrogen (δ^{15}N) stable isotope ratios in parts per thousand (‰) of the international Vienna Pee Dee Belemnite standards for carbon and atmospheric air for nitrogen, following the equation:

$$\delta X\,(\text{‰}) = \left[\left(R_{\text{sample}}/R_{\text{standard}}\right) - 1\right]$$

where R_{sample} and R_{standard} are the ratios of ^{13}C/^{12}C and ^{15}N/^{14}N of the sample and standard, respectively. We calculated delta values using multipoint normalization. The Center for Stable Isotopes at the University of New Mexico laboratory standards were soy protein, casein, tuna, whey protein, IAEA-N1, IAEA-N2, USGS-4, and USGS-43 with an analytical precision of: $\delta^{13}\text{C} < 0.04$‰ and $\delta^{15}\text{N} < 0.2$‰; the Stable Isotope Core Laboratory, Washington State University standards were acetanilide, corn, and keratin with standard deviations estimated at 0.14‰ and 0.10‰ for δ^{13}C and δ^{15}N, respectively.

Data analysis

We fitted generalized linear models with a Gaussian error distribution including latitude and year as continuous predictors and region as a categorical factor. Model assumptions were evaluated using residual diagnostic plots, and heteroscedasticity-robust standard errors were applied when violations of homogeneity of variance were detected.

We constructed isoscapes for δ^{13}C and δ^{15}N values using the geographical coordinates of each sampling location to assess variation. For manatee samples lacking detailed location information ($n = 11$), we assigned the coordinates of the mean coastal area of the state. Interpolations were then performed using ordinary kriging with spherical models. A 100 km coastal buffer was applied as a mask for improved visualization, as the species' habitat range is limited to the 10 m isobath (Normande et al. 2016).

We ran a Bayesian isotope mixing model (MixSIAR package; Stock and Semmens 2016) to evaluate spatial variation in diet composition, including region as a fixed categorical factor. We applied trophic discrimination factors of 1.8‰ for carbon, appropriate for seagrass and freshwater plant–based diets (Clementz et al. 2007), and 2.5‰ for nitrogen, reflecting the lower nitrogen trophic discrimination factor expected for sirenians compared to carnivorous marine mammals (Schoeninger and DeNiro 1984; Newsome et al. 2010). Food sources included macroalgae, mangroves, and C_4 plants. C_4 plants comprised seagrasses in the NEC (Humid + Dry-NEC) and saltmarsh vegetation in the NC.

We used the standard ellipse area corrected for small sample sizes (SEAc, ‰^{2}) to measure isotopic niche breadth of the

Table 1. Description of the study regions (Dry-NEC, Humid-NEC, and NC) including their names, locations (refers to the Brazilian states that define the boundaries of each region, except for the Dry-NEC and Humid-NEC, whose dividing point is the location known as Cabo Calcanhar, situated in the state of Rio Grande do Norte, abbreviated as RN), and coordinates; main characteristics in terms of geological, climatic, oceanographic, and plant distribution aspects and references used for area characterization.

Region	Characteristics	References
NC Amapá (02°50′S, 41°43′W) to Maranhão (04°26′N, 51°32′W)	Heavily influenced by Amazon River discharge and mud deposition. Well-developed mangroves dominated by *Rhizophora* species, several rivers, wetlands, deltas and estuaries, allowing the formation of saltmarshes. Mangrove forests do not connect to seagrasses or macroalgae beds. Seagrasses (*Ruppia maritima*) are documented only in coastal lagoons, where manatees are absent. No samples were available for Amapá.	Schaeffer-Novelli et al. (1990, 2016), Souza Filho (2005), Souza Filho et al. (2006), Giarrizzo et al. (2011), Copertino et al. (2016)
Dry-NEC Piauí (02°50′S, 41°43′W) to Cabo Calcanhar/RN (05°09′S, 35°29′W)	Arid climate with a pronounced dry season. Piauí–Ceará border encompasses a mosaic of estuaries, mangroves, seagrass meadows, and macroalgal beds, where manatees are associated with the river mouths of the Camurupim, Cardoso, Timonha, and Ubatuba. Eastern Ceará and RN present a straight coastline, dominated by sandy beaches, dunes, sandstone cliffs, high-energy waves, seagrass meadows, and macroalgal beds, with few rivers and estuaries and no bays, lagoons, or other sheltered coastal environments. Less developed mangroves. Great diversity of phanerogam species (including *Halodule wrightii*, *Halodule emarginata*, *Halophila decipiens*, *Halophila baillonis*).	Schaeffer-Novelli et al. (1990), Pinheiro-Joventino et al. (1998), Meirelles (2008), Barros and Rocha-Barreira (2014), Copertino et al. (2016)
Humid-NEC Cabo Calcanhar/RN (05°09′S, 35°29′W) to Alagoas (10°29′S, 36°25′W)	Narrow sandy beaches, sandstone reefs providing protection from high-energy dynamics, diverse coastal landscapes with rocky shores, macroalgae and seagrass beds, tidal flats with mangroves. Two well-studied protected areas where manatees occur are present in the region: the Barra de Mamanguape and Costa dos Corais environmental protection areas. The Barra de Mamanguape is characterized by sparse seagrass meadows and a fringe reef system dominated by macroalgal beds. In contrast, the Costa dos Corais and the adjacent Alagoas coast are characterized by a high diversity of coastal environments, including sandy beaches, estuaries, lagoons, and reef systems.	Figueiredo et al. (2008), Xavier et al. (2012), Copertino et al. (2016), Deeks et al. (2024b)

manatees in each of the regions using Stable Isotope Bayesian Ellipses (Jackson et al. 2011). All spatial analyses were conducted using the Spatial Analyst tool in ArcMap 10.8.1 software (ESRI 2023) and statistical and isotopic analyses were performed in the R statistical environment (R Core Team 2021).

Results

Regional differences in isotopic values

For δ^{13}C values, generalized linear models revealed a significant effect of region, while latitude and year showed no detectable influence. Relative to the Dry-NEC, manatees from the Humid-NEC had significantly lower δ^{13}C values ($\beta = -3.73 \pm 1.66$ SE, $z = -2.25$, $p = 0.025$), whereas δ^{13}C values of animals from the NC did not differ significantly from Dry-NEC ($\beta = -8.74 \pm 6.37$ SE, $p = 0.17$) (Table 2). Neither latitude ($\beta = -0.10 \pm 0.48$ SE, $p = 0.84$) nor year ($\beta = -0.02 \pm 0.05$ SE, $p = 0.68$) was significantly associated with δ^{13}C values.

δ^{15}N values of manatees were not associated with latitude ($\beta = 0.017 \pm 0.31$ SE, $p = 0.96$) or year ($\beta = -0.006 \pm 0.034$ SE, $p = 0.86$), and did not differ significantly between regions relative to Dry-NEC (HNC: $\beta = 0.78 \pm 0.95$ SE, $p = 0.42$; NC:

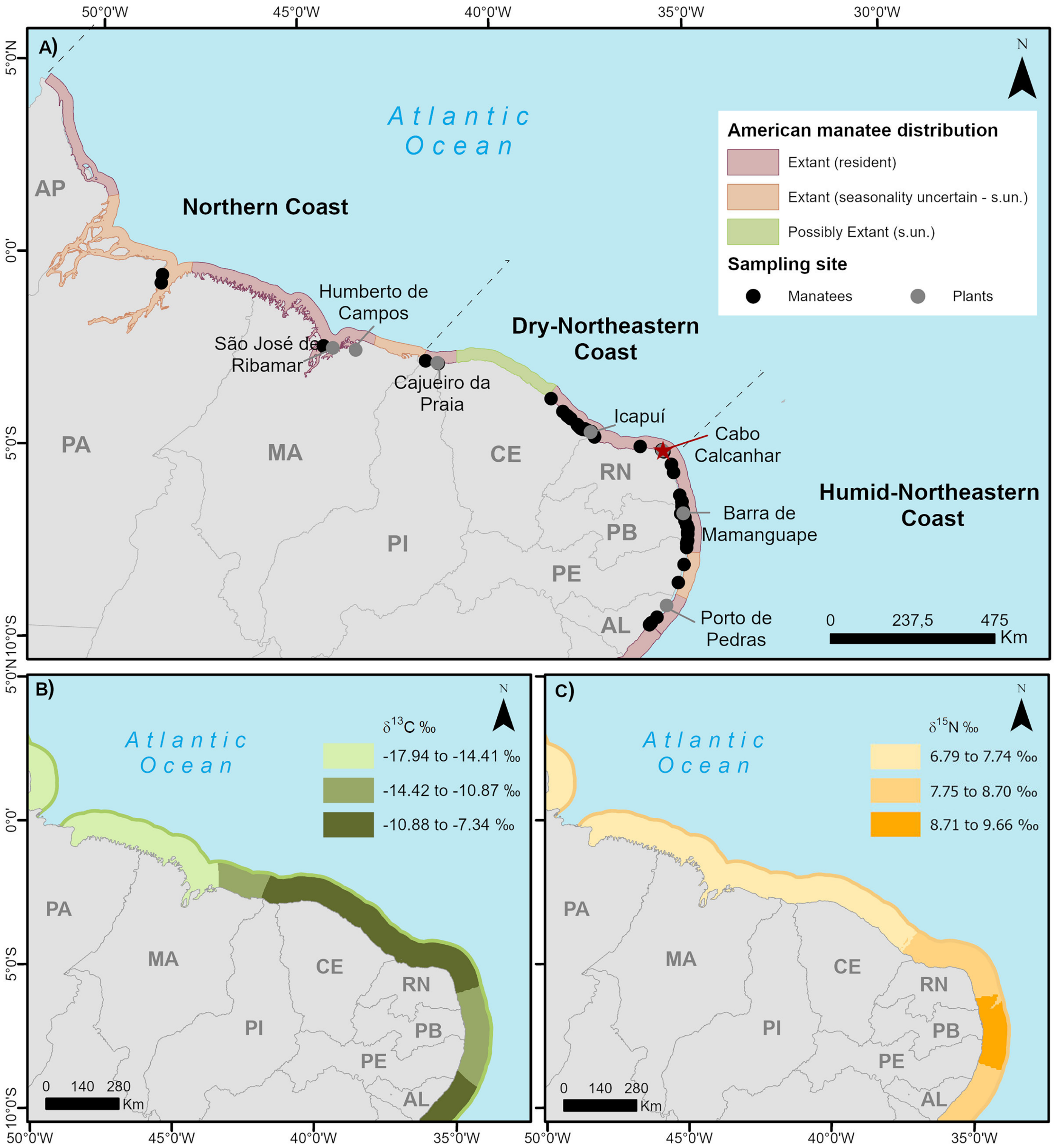

Fig. 1. (**A**) Study area showing manatee distribution according to IUCN data (Deutsch and Morales-Vela 2024), sampling locations for manatees and food sources, Brazilian states, and the division into three regions: Northern Coast, Dry Northeastern Coast, and Humid Northeastern Coast. Plant samples were collected in Humberto de Campos (MA), São José de Ribamar (MA), Salvaterra (PA), and Soure (PA) in the NC; Cajueiro da Praia (PI) and Icapuí (CE) in the Dry-NEC; and Barra de Mamanguape (PB) and Porto de Pedras (AL) in the Humid-NEC. (**B**) $\delta^{13}C$ and (**C**) $\delta^{15}N$ isoscapes produced from the interpolation of isotopic values obtained from American manatee teeth and bone samples along the Brazilian coast as shown in (**A**). AL, Alagoas; CE, Ceará; MA, Maranhão; PA, Pará; PB, Paraíba; PE, Pernambuco; PI, Piauí; RN, Rio Grande do Norte.

$\beta = -1.49 \pm 1.87$ SE, $p = 0.43$). The absence of temporal trends in isotopic values indicates temporal stability over the study period, which reduces potential bias arising from the limited temporal coverage of plant samples and supports their use as baseline inputs for MixSIAR models.

The isoscapes revealed clear regional patterns and additional spatial variability within the Humid-NEC region. Although latitude was not a significant predictor in the generalized linear models, spatial gradients indicate that manatees from the northern part of Rio Grande do Norte (RN) and the state of Alagoas (AL) had higher δ^{13}C values. The δ^{15}N values were higher along the coast between southern RN and Pernambuco (Fig. 1B,C).

Food resources and manatee diet composition

Along the NEC, seagrasses had the highest δ^{13}C values, whereas in the NC the highest δ^{13}C values were observed in saltmarsh plants. Macroalgae had the highest δ^{15}N values along the NEC, whereas in the NC, δ^{15}N values were highest in saltmarsh plants, with values comparable to those observed in macroalgae (Table 2; Supporting Information Table S2; Fig. 2A).

Because latitude was not a significant predictor in the generalized linear model analyses, it was not included as a continuous effect in the mixing models. Nevertheless, MixSIAR results revealed clear differences in manatee diet among regions (Fig. 3). In the Dry-NEC, manatees consumed almost exclusively seagrasses (mean ± standard deviation [SD]:

Table 2. Isotopic carbon and nitrogen ratios (minimum, mean ± standard deviation, and maximum) and sample size (*n*) of manatees and plant resources from three distinct regions: Dry-NEC, Humid-NEC, and NC.

		δ^{13}C (‰)			δ^{15}N (‰)		
Region/sample	***n***	**Min**	**Mean ± SD**	**Max**	**Min**	**Mean ± SD**	**Max**
Dry-NEC							
Manatee	35	−15.6	−8.4 ± 1.7	−5.9	3.9	7.8 ± 2.0	12.5
Macroalgae	23	−23.7	−18.9 ± 2.8	−13.2	3.4	6.8 ± 1.8	9.9
C_4—seagrass	6	−12.0	−10.9 ± 0.7	−10.1	3.6	4.8 ± 1.2	6.2
Mangrove	6	−28.7	−28.2 ± 0.4	−27.7	5.2	5.7 ± 0.5	6.3
Humid-NEC							
Manatee	37	−19.9	−12.0 ± 3.6	−6.9	−1.4	8.3 ± 2.5	12.3
Macroalgae	17	−20.6	−16.8 ± 2.5	−12.3	4.1	6.1 ± 1.8	9.3
C_4—seagrass	6	−14.7	−11.9 ± 2.6	−9.5	−0.2	2.8 ± 2.0	5.1
Mangrove	12	−32.4	−29.5 ± 1.8	−26.2	−0.6	2.7 ± 2.2	6.3
NC							
Manatee	7	−22.0	−16.7 ± 2.8	−13.3	5.6	6.7 ± 1.4	9.5
Macroalgae	16	−25.0	−20.1 ± 4.8	−10.8	2.9	4.9 ± 1.7	7.5
C_4—saltmarsh	3	−13.4	−13.2 ± 0.1	−13.2	2.9	5.0 ± 1.8	6.2
Mangrove	9	−29.3	−27.5 ± 1.0	−26.1	−0.4	3.9 ± 2.1	6.1

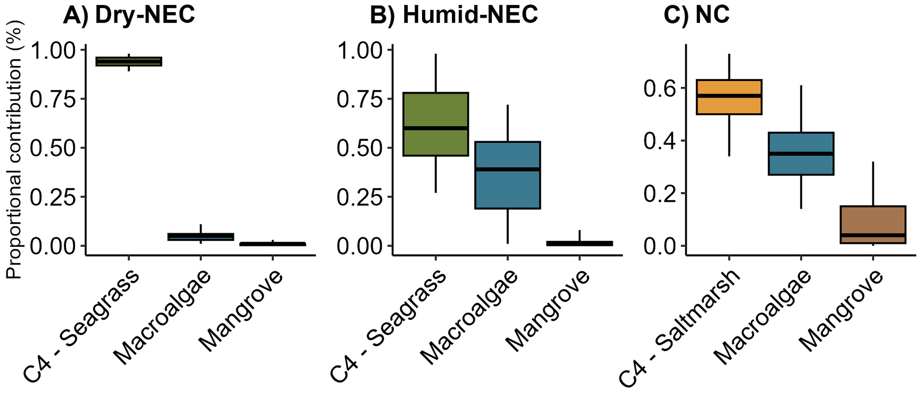

Fig. 2. Proportional contribution (%) of different plant types in the diet of the American manatees for each region using MixSIAR mixing models. (**A**) Dry-NEC, Dry Northeastern Coast; (**B**) Humid-NEC, Humid Northeastern Coast; and (**C**) NC, Northern coast.

0.94 ± 0.02), followed by macroalgae (mean ± SD: 0.05 ± 0.02) and mangrove (mean ± SD: 0.01 ± 0.01). Manatees from the Humid-NEC also consumed primarily seagrass (mean ± SD: 0.62 ± 0.20); however, macroalgae (mean ± SD: 0.36 ± 0.21) represented a substantial component of the diet, whereas mangrove contribution was negligible (mean ± SD: 0.02 ± 0.02) (Fig. 2). The NC manatees fed predominantly on saltmarsh (mean ± SD: 0.56 ± 0.10), followed by macroalgae (mean ± SD: 0.35 ± 0.12) and mangrove (mean ± SD: 0.09 ± 0.10).

Isotopic niche breadth

We found the broadest isotopic niche in manatees from the Humid-NEC (SEAc = 27.9 ‰^{2}). Manatees from the NC had SEAc = 14.5‰^{2}, whereas those from the Dry-NEC had the narrowest niche (SEAc = 11.2‰^{2}) (Fig. 2B).

Discussion

Regional differences in foraging strategies

In this study, we quantified geographic variation in δ^{13}C and δ^{15}N values and isotopic niche breadth of American manatees in relation to regional environmental characteristics. Manatees from NC, a mangrove-dominated region, strongly influenced by continental freshwater discharge and lacking seagrass beds, have the lowest δ^{13}C values. In contrast, individuals from the Dry-NEC, characterized by extensive seagrass, reduced freshwater input, and hypersaline estuaries, have the highest δ^{13}C values and the narrowest isotopic niche width, indicating a more specialized foraging strategy.

Although δ^{15}N values of manatees did not significantly differ among the regions, relatively higher δ^{15}N values in manatees from the Humid-NEC may indicate increased macroalgae consumption, as macroalgae typically exhibit elevated δ^{15}N values due to distinct nitrogen cycling processes (Cole et al. 2004). Additionally, anthropogenic nitrogen inputs to coastal systems can elevate baseline δ^{15}N values and potentially influence δ^{15}N values in manatee tissues (Lacerda et al. 2021; Val et al. 2023). By contrast, the lower δ^{15}N values observed in NC manatees, despite the consumption of nitrogen-rich sources, may indicate the relatively pristine and less urbanized nature of this region.

The stable isotope mixing model revealed that manatees from the Dry-NEC likely feed almost exclusively on seagrasses in coastal habitats, particularly *Halodule wrightii* meadows, which dominate the region (Copertino et al. 2016). These findings also suggest little to no contribution of macroalgae and mangroves. This dietary specialization likely reflects both the high availability of seagrass and the scarcity or degradation of alternative habitats. The Dry-NEC contains few riverine inputs, the largest being the Jaguaribe River (CE) and the Apodi-Mossoró and Piranhas-Açu estuaries (RN), which have been increasingly impacted by salt extraction and extensive shrimp farming (Moreira-Lima et al. 2024).

Manatees from the Humid-NEC exploit a wide range of marine, estuarine, and freshwater resources, as also indicated by telemetry data (Normande et al. 2024), resulting in the widest isotopic niche among the study regions. Macroalgae contributed substantially to the diet (~ 40%), consistent with previous observations in RN (Paludo and Langguth 2002) and Paraíba (Borges et al. 2008) states, where macroalgae represent an important food source and constitute the primary dietary item for some individuals. This pronounced dietary heterogeneity can explain the greater variability in δ^{13}C and δ^{15}N values and the broader credibility intervals observed in the MixSIAR outputs for the Humid-NEC. This high trophic diversity likely reflects spatial and temporal variation in food

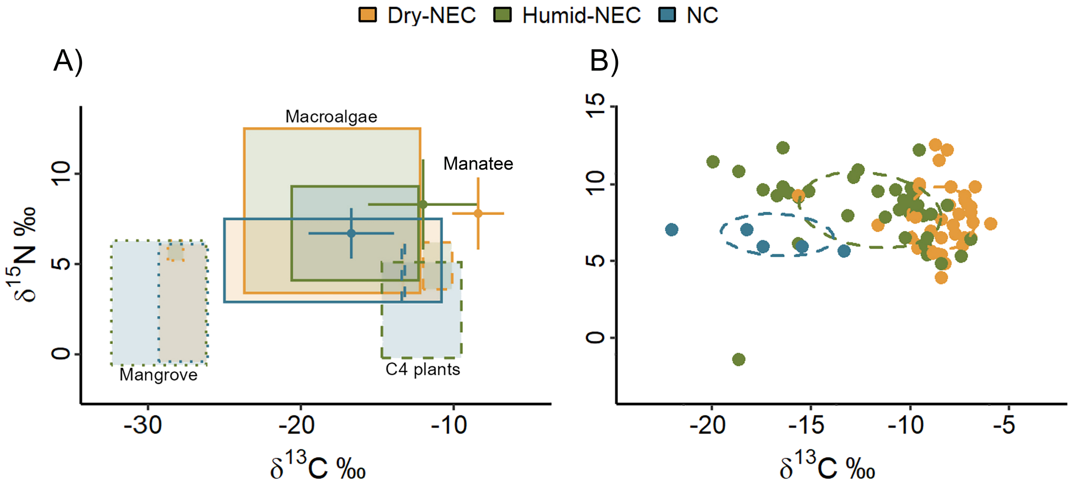

Fig. 3. (**A**) Dots and bars (crosses) represent manatees' isotopic values (mean ± standard deviation). Squares represent the minimum and maximum isotopic values for food sources in each site: Mangrove (dotted line), Macroalgae (solid line) and C_4 plants (dashed line). (**B**) Isotopic niche breadth is represented as the standard ellipse area corrected for small sample sizes (SEAc), based on δ^{13}C and δ^{15}N values from teeth and bones of American manatees across the three major regions along the Brazilian coast. Dry-NEC, orange; Humid-NEC, green; and NC, blue.

availability, since seagrass availability has declined in recent years (Deeks et al. 2024a, 2024b) and some areas into Humid-NEC present sparse seagrass meadows and reef systems dominated by macroalgal beds (Xavier et al. 2012).

Despite this trophic plasticity, manatees generally prefer seagrasses when available (Provancha and Hall 1991; Alves-Stanley et al. 2010; Garcés-Cuartas et al. 2025), in line with sirenian foraging strategies driven by palatability, digestibility, and nutritional quality (Heinsohn and Birch 1972; Hartman 1979). *Halodule wrightii*, in particular, is nutritionally important due to its high fiber and protein content (Rodrigues et al. 2021; Arévalo-González et al. 2024). Seasonal and environmentally driven variation in food resources distribution may further shape diet composition, as documented in Costa Rica and for Amazonian manatees (*Trichechus inunguis*) (Guterres-Pazin et al. 2014; Cubero-Pardo et al. 2024).

In NC, where seagrasses are absent, manatees have a mixed diet composed primarily of saltmarsh plants, followed by macroalgae, consistent with previous research in the region (Lins et al. 2014; Carvalho et al. 2022). Isotopic niche analyses indicate an intermediate level of dietary and habitat diversity between the Dry-NEC and the Humid-NEC. This pattern may result from the strong influence of freshwater inputs on coastal marine areas or reflect sampling limitations associated with a relatively small sample size ($n = 7$).

Methodological constraints and limitations

It is important to note that natural discontinuities in the species' distribution (Fig. 1) resulted in more samples from areas with higher manatee abundance. Sample availability was largely opportunistic rather than driven by a predefined sampling design, reflecting the inherent challenges of obtaining biological material from manatees, particularly given the rarity of records of stranded adult individuals. Although this unique dataset represents one of the largest compilations of samples from American manatees in Brazil, the uneven sampling may nevertheless introduce spatial bias and reduce the representativeness of under-sampled regions. In regions with sampling gaps, interpolation may yield less refined predictions, which could be improved by incorporating additional samples in future research.

Implications for conservation

Understanding spatial variation in resource use and availability across the distributional range of endangered consumers is critical for effective conservation planning. In Brazil, rescue, rehabilitation, and release programs have been implemented as key strategies for protection of American manatees (Normande et al. 2015; Santos et al. 2023). The detailed dietary information is particularly valuable for identifying suitable release sites and for monitoring post-release movements, habitat use, and survival, especially as released individuals explore new or previously unoccupied areas.

Beyond informing release strategies, dietary data also contribute to the identification of critical habitats based on manatee feeding resources, highlighting that macroalgal beds and saltmarshes should be considered as important as seagrass meadows for the long-term maintenance of the species. In Brazil, these ecosystems are under increasing pressure from multiple anthropogenic threats (Schaeffer-Novelli et al. 2016; Goldberg et al. 2020; Soares et al. 2022). Seagrass meadows have declined by up to 50% in some regions (Short et al. 2006; Pitanga et al. 2012; Deeks et al. 2024b), with global loss rates accelerating since the 1940s (Waycott et al. 2009; de los Santos et al. 2019) and further declines projected under climate change scenarios (Daru and Rock 2023; Gouvêa et al. 2025). Similar trajectories are expected for macroalgae and saltmarshes, exacerbated by nitrogen inputs, aquaculture, invasive species, and coastal development (Cole et al. 2004; Copertino et al. 2016). Despite their ecological relevance, these habitats remain poorly mapped and monitored, highlighting the urgent need for standardized methodologies to map and assess macroalgal beds, seagrass meadows, and saltmarshes (Copertino et al. 2016; Karez et al. 2026).

Conclusions

Our comprehensive analysis of the trophic ecology of American manatees across the Brazilian coast revealed substantial differences across the NC, Dry-NEC, and Humid-NEC regions. Manatees from areas with greater habitat diversity and resource availability, such as the Humid-NEC and NC, have more generalist diets and wider trophic niches, whereas animals from regions characterized by high seagrass availability and more degraded estuaries, such as the Dry-NEC, are more specialized and rely predominantly on marine environments.

Given that habitat suitability for manatees is expected to decline and that the magnitude of these impacts will likely vary regionally according to dietary composition, populations with more specialized diets and limited access to alternative food resources may face disproportionately higher risks. We therefore recommend explicitly incorporating manatee habitat-use patterns and primary food resources into coastal conservation planning and management strategies. Integrated actions—including stronger legal protections, new marine protected areas, restoring and effective mitigation of human impacts—are critical if we are to secure the long-term viability of this emblematic species and its ecosystem services.

Author Contributions

Miriam Marmontel, Fábia de Oliveira Luna, Fernanda Niemeyer Löffer Attademo, Vitor Luz Carvalho, João Carlos Gomes Borges, Alexandra Fernandes Costa, and Renata Emin-Lima conducted the field work collecting manatee samples between the years 1989 and 2018. Leandro L. Ciotti and Camila Carvalho de Carvalho sorted tooth samples from

scientific collections and prepared them for chemical analysis. Leandro L. Ciotti, Camila Carvalho de Carvalho, and Alexandra Fernandes Costa collected and prepared plant samples. All authors generated research questions and designed the study. Camila Carvalho de Carvalho, Leandro L. Ciotti, and Emma Deeks conducted statistical analyses, created figures, and prepared the original draft of the manuscript.

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Conflicts of Interest

The authors report no conflicts of interest.

Data Availability Statement

Data and metadata are available in the Zenodo data repository at https://zenodo.org/records/15616287.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

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