Hydrobiologia (2023) 850:1237–1249
https://doi.org/10.1007/s10750-022-05086-2

TRENDS IN AQUATIC ECOLOGY IV

Opinion Paper

Are stable isotopes an efficient tool for tracking the effect of anthropogenic activities on mangrove food web structure and function?

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Received: 7 May 2022 / Revised: 1 November 2022 / Accepted: 8 November 2022 / Published online: 8 December 2022

Abstract Understanding and connecting the impact of anthropogenic activities on mangrove food webs is a research challenge. Has research on the subject been able to find answers using stable isotopes? The present opinion paper analyzed the utility of stable isotopes in tracing the impact of anthropogenic activities on mangrove food webs and if the research questions raised could be answered using these chemical markers. Representative research papers (16) focused on the use of stable isotopes (δ^{13}C, δ^{15}N, δ^{34}S, δ^{2}H, δD,206Pb/207Pb, and 208Pb/207Pb) to evaluate the effect of anthropogenic activities (Sewage discharge, timber harvesting–deforestation, metallurgical activities, hydrological disruption, aquaculture ponds, and urban development) on mangrove food webs were selected. Each article included at least one group of consumers (invertebrate or fish). Publications only focused on water quality or primary producers were not included. Most studies managed to determine the effect of the anthropogenic activities on the food web's stable isotope values. Based on the above, we concluded that these markers are an effective tool to determine affectation patterns on the structure and function of mangrove food webs. The results obtained herein facilitate the correct management of mangroves and their derived resources.

Keywords Isotopic modeling · Ecosystem management · Trophic ecology · Mangrove trophic flows

Introduction

Mangrove forests are recognized for their important functional and structural characteristics. It is widely documented that these ecosystems are exporters or carbon sequesters, nursery areas, shoreline protectors, land builders, and climate change mitigators (Nagelkerken et al., 2008; Lee et al., 2014; Adame et al., 2021) among other vital ecosystem services for human communities (Palacios & Cantera, 2017). In coastal areas anthropogenic activities converge at various levels (subsistence, artisanal, and industrial), affecting mangrove function (Erazo & Bowman, 2021) and reducing their area (Wolanski et al., 2000). These activities include sewage discharges, timber extraction, aquaculture, agriculture, infrastructure construction, fishing, and tourism, among others (Valiela et al., 2001; Adame et al., 2021).

In the last decades, high levels of degradation and loss of mangrove ecosystems have occurred

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Guest editors: Koen Martens, Sidinei M. Thomaz, Diego Fontaneto & Luigi Naselli-Flores / Emerging Trends in Aquatic Ecology IV

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due to anthropogenic activities, especially in tropical regions. Between 1980 and 2000, at least 35% of global mangrove cover has been lost, equating to more than that of tropical forests and coral reefs (Valiela et al., 2001). Due to pond culture, 58% of mangrove cover in the Philippines were lost, 50% in Thailand (Primavera, 1993) and 50–80% in Southeast Asia (Wolanski et al., 2000). Due to shrimp farming, 28–40% of mangrove cover was lost in Ecuador between 1970 and 2006 (Ashton, 2008). Moreover, it is estimated that by the end of the century (2010–2100), the main causes of degradation and loss of mangrove function will be agriculture and aquaculture in Tropical Eastern Pacific, Temperate South America, and Central Indo-Pacific regions; erosion in Western and Central Indo-Pacific and Tropical Atlantic, clearing in Temperate Australasia, Central and Western Indo-Pacific, and Tropical Atlantic; and climate events in Temperate Australasia (Adame et al., 2021).

Anthropogenic modification of mangrove ecosystems contribute to decreased habitat quality, potentially affecting food web structure and function (Taylor et al., 2007; Bui & Lee, 2014; López-Rasgado et al., 2016; Medina-Contreras et al., 2021). Stable isotopes have been used for 4 decades to study mangrove food webs. The analysis of these markers (δ^{13}C and δ^{15}N) allows for the identification of primary producer sources and foods for consumers and has been extensively used as a tool for assessing ecological trophic relationships (Bouillon et al., 2011; Layman et al., 2012).

Initially, the studies determined the importance of mangrove carbon for consumers of tropical and subtropical systems (Rodelli et al., 1984; Zieman et al., 1984), principally species of fishery importance (Stoner & Zimmerman, 1988; Harrigan et al., 1989). The number of publications that study mangrove food webs using these chemical markers increased considerably, becoming relatively numerous during the previous 4 decades (>80). The most recurrent research questions are which autotrophic sources sustain mangroves food webs? (Nyunja et al., 2009; Sepúlveda-Lozada et al., 2015; Medina-Contreras et al., 2018); how important is mangrove-derived carbon to certain species, groups, or assemblages? (Abrantes et al., 2015); and what is the spatial scope of mangrove organic carbon as a food source for consumers of estuarine food webs? (Rodelli et al., 1984; Mendoza-Carranza et al., 2010; Claudino et al., 2015).

Studies of the effect of anthropogenic activities on mangrove food webs through the use of stable isotopes has been limited (Hadwen & Arthington, 2007), with most of the research developed from 2010, but is becoming a subject of growing interest. The main objective of these studies has been to examine nitrogen and carbon flow patterns through the mangrove food webs with some anthropogenic alteration; for example, deforestation (Viana et al., 2015; Then et al., 2020), sewage inputs (Hadwen & Arthington, 2007; Medina-Contreras et al., 2021), and hydrological disruption (López-Rasgado et al., 2016), among others. These studies hypothesized that anthropogenic habitat modification leads to differences in niche and trophic structure of mangrove communities and hence trophic function.

In this opinion paper, representative research papers from different oceanic regions (Spalding et al., 2007) focused on the use of multiple stable isotopes (δ^{13}C, δ^{15}N, δ^{34}S, δ^{2}H, δD, 206Pb/207Pb, and 208Pb/207Pb) to evaluate the effect of anthropogenic activities on mangrove food webs were selected and reviewed. With the objectives of (1) analyzing if stable isotopes are effective tracers to evaluate the effect of anthropogenic activities on mangrove food webs and (2) conclude whether stable isotopes were useful to answer the research questions and to evaluate raised hypotheses.

Why use stable isotopes to track the effect of anthropogenic activities on mangrove food webs?

As will be discussed throughout this opinion paper, isotopic composition, trophic position, isotopic niche, and food web pathways may vary depending not only on mangrove environmental settings (Abrantes et al., 2015) but also on human modification of the habitat. For example, striking differences in the isotopic composition and niche of dominant fish communities of tropical and subtropical mangroves with different levels of anthropic intervention have been found (López-Rasgado et al., 2016; Mwandya, 2019; Medina-Contreras et al., 2021). The conservation status of mangroves could also have an effect on the connectivity between ecosystems (coral/rocky reefs), affecting ontogenetic fish movements between them (López-Rasgado et al., 2016; Medina-Contreras et al., 2021). Moreover, large-scale mangrove forest clearing may impact estuarine food webs, with potential consequences to nearby coastal ecosystems (Fraga et al., 2018).

According to this, stable isotopes principally δ^{15}N and δ^{13}C values potentially could track the anthropogenic effects on mangrove food webs. Regarding δ^{15}N, this parameter could be an indicator of the alteration of water quality. In general, higher concentrations of ^{15}N are usually found in intervened mangrove systems compared to moderate or non-intervened mangroves (Hadwen & Arthington, 2007; Souza et al., 2018; Medina-Contreras et al., 2021), possibly due to the influence of waters loaded with nitrites, nitrates, and ammonium from various anthropic activities developed in bays, estuaries, and creeks associated to mangroves.

The δ^{13}C values are widely used as indicators of differences in the sources of organic carbon used by consumers. Patterns of ^{13}C enrichment/impoverishment and its relation to anthropogenic activities are not entirely clear (Medina-Contreras et al., 2021). For example, mangroves systems subject to hydrological restriction and deforestation exhibit different ^{13}C values compared to non-intervened mangroves (López-Rasgado et al., 2016; Mwandya, 2019); however, the magnitude and tendency of these differences are particular for every study case as will be discussed later.

Papers selection criteria

A search was made in different databases of scientific citations, specifically Google Scholar and Scopus. The search keywords were *mangrove anthropogenic intervention*, *stable isotopes*, *trophic structure of intervened mangroves*, and *stable isotope models in disturbed mangroves*. The time range of the search was from 1980 to 2021. The selected papers had the following characteristics: (1) their main objective had to be to evaluate or understand the effect of anthropogenic activities on mangrove food webs. (2) They had to include at least one group of primary or secondary consumers (macroinvertebrates or fish, not bacteria or fungi). (3) They should include isotopic values and analysis of mangrove leaves. (4) Articles that only analyzed primary sources or basal resources (i.e., Particulate organic matter, Mangroves, Algae) were not included, even if they sought to identify contamination using stable isotopes, since the main objective of this opinion paper was not to analyze the efficiency of stable isotopes to track mangrove water quality or nutrient levels. (5) Only in situ research was included, not experiments. (6) The studies had to be carried out in mangrove creeks and not in large estuaries far from mangrove areas.

Anthropogenic actions evaluated

The following anthropogenic activities affecting mangrove food webs were evaluated in the selected papers (Fig. 1): sewage discharges, timber harvesting and/or deforestation, hydrological disruption, urban development, waste deposition from metallurgical activities, and aquaculture ponds (Table 1). Others were listed as part of the anthropogenic activities developed in anthropogenically intervened systems which potentially affect the structure and function of mangrove food webs. For example, tourism, shell harvesting, fishing, solid waste deposition, and recreation among others. However, its effect on mangrove food webs was not particularly evaluated.

Sewage discharge

The studies that evaluated the effect of sewage discharges on mangrove food webs hypothesized that the δ^{15}N values in food web components (primary producers and consumers) are higher in mangroves with sewage inputs compared to those without them (Hadwen & Arthington, 2007; Pitt et al., 2009; Mazumder et al., 2015; Zulkifli et al., 2016; Samper-Villarreal et al., 2018; Souza et al., 2018; Lugendo & Kimirei, 2021; Medina-Contreras et al., 2021). The elevation of nitrogen levels has the potential to alter the structure and function of mangrove ecosystems. As a result, stable nitrogen isotope analysis (δ^{15}N) has emerged as an effective way of exploring the effects of anthropogenic N uptake by mangrove food webs (Mazumder et al., 2015). These studies through δ^{15}N values indicate that sites with sewage discharges present ^{15}N enrichment in sediments, primary producers (algae and mangroves), and consumers (invertebrates and fish). This pattern of ^{15}N enrichment can also be observed by comparing sites categorized as non-polluted and moderate, indicating that δ^{15}N is highly sensitive to the increase in N of anthropogenic origin in mangroves and creeks (Lugendo & Kimirei, 2021).

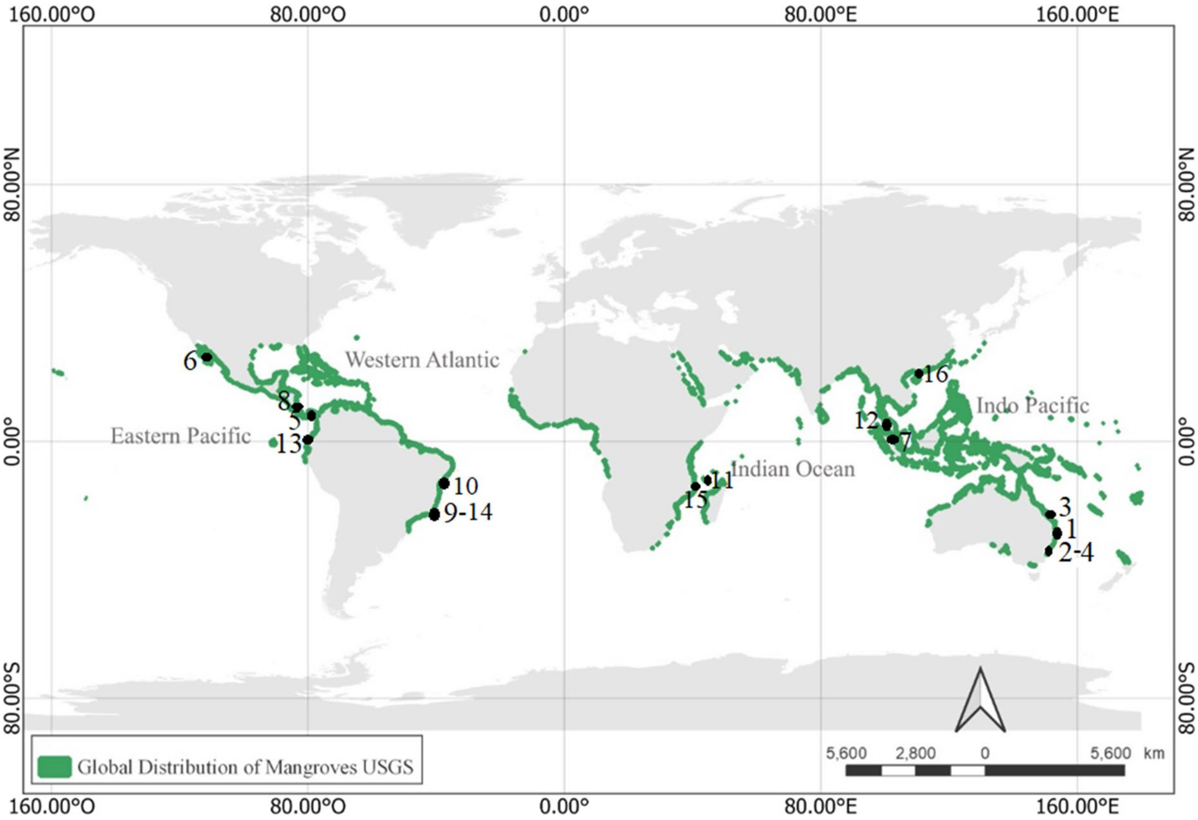

Fig. 1 Geographical location of selected research that has analyzed the effect of anthropogenic activities on mangrove food webs. The numbers correspond to studies from the oldest (1) to the most recent (16). **(1):** Tallow and Belongil Creeks, Australia (Hadwen & Arthington, 2007); **(2):** Annandale Wetland, Australia (Sheaves et al., 2007); **(3)** Moreton Bay, Australia (Pitt et al., 2009); **(4)** Botany and Homebush Bays, Australia (Mazumder et al., 2015); **(5)** Chiriquí Gulf, Panamá (Viana et al., 2015); **(6):** La Paz Bay, México (López-Rasgado et al., 2016), **(7)** Puloh River, Malaysia (Zulkifli et al., 2016); **(8)** Dulce Gulf, Costa Rica (Samper-Villarreal et al., 2018), **(9)** Vitória and Santa Cruz Bays, Brasil (Souza et al. 2018); **(10)** Piraquê-Açu-Mirim Estuary, Brasil (Fraga et al., 2018), **(11)** Makoba and Chwaka Bays, Tanzania (Mwandya, 2019), **(12)** Mantang mangrove forest reserve, Peninsular Malaysia (Then et al., 2020), **(13)** Buenaventura and Málaga Estuaries, Colombia (Medina-Contreras et al., 2021), **(14)** Vitória and Santa Cruz Bays, Brasil (Souza et al., 2021), **(15)** Dar es Salaam and Pawani mangroves, Tanzania (Lugendo & Kimirei, 2021), and **(16)** Qinglan Mangrove Nature Reserve, China (Herbeck et al., 2021). World mangroves distribution (Giri et al., 2010) and oceanic regions (Spalding et al., 2007)

Moreover, Mazumder et al., (2015) demonstrated the decrease of food-chain length in sites with sewage discharges identifying one of the effects of nitrogen elevation on the structure of the food webs.

Another study suggests that sewage-derived nitrogen had been widely assimilated by producers and had been transferred through all trophic levels of the food web (Hadwen & Arthington, 2007). In this study, the authors also attribute ^{15} N enrichment to the hydrological conditions of the systems, which are intermittently open with a restricted circulation of water, indicating that the food webs of mangroves with this partial circulation setting are highly vulnerable to the effects of sewage discharges. This work presented strong evidence of the assimilation and trophic transfer of nitrogen effluent throughout the food web to the top consumers. Enrichment in ^{15} N (~ 1–3%) was also detected in tropical mangrove fish tissues, characterized by high anthropogenic impact, including sewage discharges, in contrast to a relatively pristine system (Medina-Contreras et al., 2021).

Other studies (Samper-Villarreal et al., 2018; Souza et al., 2018) also indicated ^{15}N enrichment in primary producers' tissues. For example, in Costa Rica (Samper-Villareal et al., 2018), mangrove leaf isotopic values showed enriched ^{15}N at nutrient-loaded

Table 1 Selected research evaluating the effect of anthropogenic activities on mangrove food webs, using stable isotopes

Oceanic Region	Country	Locality	Primary anthropogenic activity evaluated	Stable isotopes used to evaluate the effect of anthropogenic activities on mangroves food webs	References
Indo-Pacific	Australia	Tallow and Belongil Creeks	Sewage discharged	δ^{13}C and δ^{15}N	Hadwen & Arthington (2007)
Indo-Pacific	Australia	Annandale wetland	Urban development	δ^{13}C and δ^{15}N	Sheaves et al. (2007) Sheaves et al. (2007
Indo-Pacific	Australia	Moreton bay	Sewage discharged	δ^{15}N	Pitt et al. (2009)
Indo-Pacific	Australia	Brisbane water; botany and homebush bays	Sewage discharged	δ^{13}C and δ^{15}N	Mazumder et al. (2015)
Eastern Pacific	Panamá	Chiriquí gulf	Deforestation	δ^{13}C and δ^{15}N	Viana et al. (2015)
Eastern Pacific	México	California gulf	Hydrological disruption	δ^{13}C and δ^{15}N	López-Rasgado et al. (2016)
Eastern Pacific	Costa Rica	Dulce gulf	Sewage discharged	δ^{13}C and δ^{15}N	Samper-Villarreal et al. (2018)
Eastern Pacific	Colombia	Bahía Málaga and Buenaventura Bays	Timber harvesting Sewage discharged	δ^{13}C and δ^{15}N	Medina-Contreras et al. (2021)
Western Atlantic	Brasil	Vitória and Santa Cruz Bays	Metallurgical activities Sewage discharged	δ^{13}C, δ^{15}N, 206Pb/207Pb, 208Pb/207Pb	Souza et al. (2018)
Western Atlantic	Brasil	Piraquê-Açu-Mirim Estuary	Deforestation	δ^{13}C	Fraga et al. (2018)
Western Atlantic	Brasil	Vitória and Santa Cruz Bays	Metallurgical activities	δ^{15}N	Souza et al. (2021)
Indian Ocean	Malaysia	Puloh River	Sewage discharged	δ^{13}C and δ^{15}N	Zulkifli et al. (2016)
Indian Ocean	Tanzania	Makoba and Chwaka Bays	Deforestation Aquaculture ponds	δ^{13}C and δ^{15}N	Mwandya (2019)
Indian Ocean	Malaysia	Matang Mangrove Forest Reserve	Timber harvesting	δD, δ^{13}C, δ^{15}N	Then et al. (2020)
Indian Ocean	Tanzania	Dar es Salaam and Pawani mangroves	Sewage discharged	δ^{15}N	Lugendo & Kimirei (2021)
Indian Ocean	China	Qinglan Mangrove Nature Reserve	Aquaculture ponds	δ^{15}N	Herbeck et al. (2021)

mangroves, whereas algae and bivalves showed a small variation between reference and nutrient-loaded mangroves. In Brazil (Souza et al., 2018), the results indicated that the lower components of the food web, especially mangroves exhibited enriched ^{15}N in nutrient-loaded mangroves, which are more affected than organisms of higher trophic positions (crabs, oysters, shrimps, and fish). These studies also indicate that along with sewage discharges, the hydrological and geomorphological characteristics of the mangrove system also influence the assimilation of nitrogen from anthropogenic sources throughout the food web (Medina-Contreras et al., 2021). Similar to the mangrove systems in Australia (Hadwen & Arthington, 2007), the results of Samper-Villarreal et al., (2018) in Costa Rica were obtained in a system of long water residence time, contrasting a deep system with a fjord-like bathymetry and naturally low nutrient levels. The results obtained in Costa Rica provide isotopic evidence of subtle nutrient enrichment in these mangrove habitats, despite limited evidence of nutrient loading from water quality analyses. These findings are suggestive of chronic low-level nutrient loading in the study area.

In Brazil, Souza et al. (2018) found differences in the primary producers that support fish and oysters from mangroves with sewage discharge and without them. They also found ^{15}N enrichment in mangrove tissues from the site with sewage discharges. The authors suggest that these results are not only due to differences in anthropogenic pressures but also to the hydrological characteristics of each site under study, since one has greater influence from marine water, which in turn reduces the suspended sediment load, directly affecting the food source of Oysters. These results are evidence that studies that aim to determine the effect of sewage discharges on the mangrove food web should involve or consider the hydrology and geomorphology of the systems.

The previous studies showed that systems with less circulation (intermittently open) incorporate nitrogen from sewage discharges along the entire food web (Hadwen & Arthinton, 2007). Deep (Samper-Villarreal et al., 2018) or open circulation sites (Souza et al., 2018) will initially exhibit ^{15}N enrichment in their primary producers and with time anthropogenic nitrogen will also be incorporated into other food web constituents, including top consumers (Samper-Villarreal et al., 2018). According to this, Pitt et al. (2009) studied the effects of wastewater treatment plant upgrades on the utilization of sewage-N by mangrove–estuarine primary producers (filamentous algae and mangrove leaves) and consumers (shore crabs) using δ^{15}N values. The authors concluded that although the total N discharged into the study sites decreased by more than 80% after the upgrades had occurred, the δ^{15}N values of mangrove leaves remained elevated in all rivers, indicating that sewage-N remained a major source for mangroves, either from sewage discharges or from N accumulated in the sediments over many years.

The mobility of toxic trace elements (Cr, As, Cd, and Pb) from sewage discharges via terrestrial and marine anthropogenic activities and its relationship with δ^{15}N was studied on mangrove food webs of Puloh River in Malaysia (Zulkifli et al., 2016). Through the study of the giant mudskipper [*Periophthalmodon schlosseri* (Pallas, 1770)], a carnivorous fish living in mudflats and mangrove ecosystems, the authors used δ^{15}N values to assess the impact of biomagnification of toxic trace elements in food webs of mangrove creeks. The authors suggested that biomagnification was possibly occurring due to the increase of trophic levels and compared the δ^{15}N values with the concentration of selected toxic trace elements of each biological sample. The study concluded that the mobility of toxic trace elements is strongly related with δ^{15}N values. The significant relationship between both parameters served as a tool to prove that biomagnification occurs in the mangrove forest under study.

The results of the previous studies suggest that δ^{15}N values are good indicators of changes in mangrove ecosystem water quality, since nutrient enrichment can lead to elevated ^{15}N. Therefore, this parameter can be used to distinguish between clean and polluted mangrove aquatic systems. By demonstrating that the highest δ^{15}N values in a mangrove ecosystem are associated with anthropogenic discharges, the effect of these on the trophic dynamics of the ecosystem can be evaluated with such markers. Mangroves of impacted systems incorporate anthropogenic nitrogen of higher δ^{15}N values into their tissues, therefore these plants could be used to distinguish between clean and polluted mangrove estuaries. Sewage discharges modify the structure of mangrove food webs, deteriorating their food web's function and ecosystem services. For a better understanding of the effect of sewage discharges on mangrove food webs, it is necessary to develop studies in mangroves from different regions around the globe, including diverse patterns of geomorphology and environmental settings and involving seasonal variations.

Timber harvesting and deforestation

Within selected papers, studies evaluating the effect of timber harvesting and/or deforestation on mangrove food webs using stable isotopes were less compared to those that evaluated sewage discharges (Viana et al., 2015; Fraga et al., 2018; Mwandya, 2019; Then et al., 2020; Medina-Contreras et al., 2021). Some specifically analyzed the effect of deforestation and timber harvesting on the structure of mangrove food webs (Viana et al., 2015; Fraga et al., 2018; Mwandya, 2019; Then et al., 2020), while others list timber harvesting as one of the anthropogenic activities that characterize a highly impacted mangrove (Medina-Contreras et al. 2021) in a comparison of their aquatic communities' trophic structure with that of less affected mangrove systems.

In the Pacific of Panama the effect of watershed deforestation on food webs within the receiving mangrove estuaries was evaluated (Viana et al., 2015).

This study was developed in eight tropical mangroves that received inputs from watersheds with different percentages of deforestation (23%, 29%, 47%, 73%, 91%, and 92%) where the isotopic values (δ^{13}C and δ^{15}N) of consumers (fish and invertebrates) were compared. The results suggest that δ^{13}C and δ^{15}N values of consumers tissues collected from the estuaries with different percentages of deforestation were remarkably similar. Although a subtle difference in stable isotopic values of some consumers was found, the links to watershed deforestation were not evident. Due to the components of the food web being collected at the mouth of the mangrove estuaries, their isotopic signals were not affected by the degree of deforestation of the contributing watershed.

However, the authors point out that although the effect of deforestation could not be evidenced in the consumers' isotopic composition, the impact of these ecosystems by deforestation cannot be ignored. In these same Panamanian estuaries, the deforestation degree significantly affected amounts of dissolved and particulate materials released into the fresh reaches. It appears that the biogeochemical transformations taking place within mangrove estuaries are powerful enough to erase the footprint of the contributing watershed during the transit of waters and materials downstream (Viana et al., 2015). The analysis of consumers from the mudflats and forests may have evidence of the effect of deforestation on the mangroves' food webs.

The other study directly focused on timber harvesting–deforestation and used a multi-isotope approach (δ^{13}C, δ^{15}N, and δD) to trace ecosystem responses to forest clearing and replanting in a tropical mangrove forest reserve at Matang, Malaysia (Then et al., 2020). This study sampled four macroinvertebrate taxa (barnacles, prawns, gastropods, and crabs) in mangrove forests of different ages, including a reference site that has experienced little harvesting. The objectives were to determine whether a multi-isotope approach could track ecological changes of mangrove functional support of food webs and determine the timing of isotopic shifts that signal critical transitions in restoration success.

Unlike research in Panamá, this study (Then et al., 2020) could determine differences in the food web due to a deforestation gradient of 70 years. A functional food web recovery was indicated by a decrease in δ^{13}C and δ^{15}N, as well as an increase in δD for gastropods and crabs in older forests. For the benthic mangrove food webs, the δ^{13}C and δD values were practical for tracking changes in forest floor resources. For example, the open younger forests (0–5 years) received high sunlight exposure which likely promoted benthic microalgae growth and increased utilization of microalgal food sources (including phytoplankton) caused higher δ^{13}C and lower δD values in tissues of gastropods and crabs. The study also concluded that the time of a mangrove food web recovery is between 5- and 15-year post-clearing of mangroves.

In another study, changes in benthic macrofaunal assemblages and food webs at a deforested mangrove and natural site in a tropical estuary in Eastern Brazil were evaluated (Fraga et al., 2018) using δ^{13}C values. The results suggested that benthic assemblage composition, infaunal δ^{13}C signatures, and food web diversity markedly differed at the impacted site being strongly related to sedimentary changes. The authors concluded that large-scale mangrove forest clearing may impact estuarine food webs, with potential consequences to nearby coastal ecosystems.

Finally, δ^{13}C and δ^{15}N values from undisturbed mangrove creeks were compared with clear-cut areas of mangroves to understand the effects of deforestation on trophic structure of mangrove-associated fish species, in Makoba and Chwaka Bays, Tanzania (Mwandya, 2019). Results suggest that stable isotope values (δ^{13}C and δ^{15}N) in fish muscles indicated significant diet shifts between undisturbed and disturbed mangrove creeks, although the effects were species specific. For example, *Mugil cephalus* Linnaeus, 1758 collected from unforested mangroves had significantly lower ^{15} N values than individuals collected in forested mangroves, due to a change in diet from omnivore to herbivore. Similarly, lower ^{15}N values in samples of *Gerres oyena* (Forsskål, 1775) from disturbed creeks indicate a change from a fish-based diet to increased benthos. In accordance with Medina-Contreras et al. (2021) and Then et al. (2020), the results obtained (Mwandya, 2019) indicated that mangrove deforestation has a greater impact on the trophic structure of mangrove creeks' fish communities. The authors also suggest that in conjunction with land-use changes, the effects of deforestation on the trophic structure of mangrove fish communities is exacerbated (Mwandya, 2019). According to the previous papers, isotopic values of consumers' tissues are functional indicators of ecosystem changes occurring in food webs, vegetation cover, and soils.

Metallurgical activities

The effect of the deposition of residues from metallurgical activities on mangrove food webs through stable isotopes was analyzed through two studies (Souza et al., 2018, 2021) from Brazil. The articles hypothesized that the evaluation of multiple stable isotopes in mangrove ecosystems allows for linking anthropogenic activity to different levels and sources of contamination. The authors employed volatile stable isotopes (δ^{13}C, δ^{15}N) which are commonly used for the evaluation of pollutant plumes in groundwater and non-volatile stable isotopes (87Sr/86Sr, 206Pb/207Pb and 208Pb/207Pb) which used less frequently. These isotopes were measured in sediments, mangroves, plankton, shrimps, crabs, oysters, and fish from three mangrove areas with different levels of anthropogenic impact and sources of contamination. According to this research (Souza et al., 2018), the combined use of both volatile and non-volatile stable isotopes is uncommon but highly valuable for identifying sources of environmental contaminants in estuarine mangrove systems affected by anthropogenic and industrial pollution (Souza et al. 2018).

The analysis of 206Pb/207Pb and 208Pb/207Pb ratios confirmed that the Pb isotope values in all sampling sites were similar to sites with typical metallurgical activities (Souza et al., 2018, 2021). The authors suggest that this result is due to the presence of anthropogenic aerosols containing Pb from industrial sources, such as mining, smelting, coal burning, crushing, grinding, separation, refining, and residue management. One of the three study sites exhibited the highest Pb isotopic ratios (206Pb/207Pb and 208Pb/207Pb) for sediment, mangroves, and crabs due to the presence of solid waste from metallurgical activities, affecting mainly sediments and the benthic components of the food web. Finally, the study concludes that three out of five measured isotopic ratios (206Pb/207Pb; δ15N and 87Sr/86Sr) were sufficient to indicate differences between the studied areas, and as metal/metalloid contamination can originate from several sources, stable isotope ratios have been used to identify the origin (source) of metals and metalloids in the mangrove food webs (Souza et al., 2018).

Additionally, most metals were biomagnified through the mangrove food web and were found in all trophic levels (Souza et al., 2021). Due to the similar trophodynamics of non-polluted and polluted mangroves and the unequal transfer patterns in other cases, the effectiveness of ^{15}N to study food webs with aquatic biota affected by anthropogenic contaminants is questionable.

Hydrological disruption

The effects of hydrological disruption caused by anthropogenic activities on mangrove food webs using stable isotopes were analyzed in a single study (López-Rasgado et al., 2016) in the Gulf of California, where mangrove systems are under serious threat due to the construction of shrimp farms and tourism development. Here the authors examine the relationship between the degree of anthropogenic modification of three mangrove systems and the isotopic trophic structure of the dominant fish community. The study areas included a natural system that has not been subject to habitat modification, a slightly impacted mangrove by possible urban expansion, and a highly impacted mangrove with a severe limitation of water exchange with the adjacent bay due to road construction and heavily modified by anthropogenic activities.

The results indicate that δ^{13}C values of most fish caught within the highly impacted mangrove were greater than those in systems impacted at a lesser degree (López-Rasgado et al., 2016). The hydrological disruption may lead to a high dependence of the fish community on autochthonous carbon. As indicative of high functional trophic redundancy and a more compact food web, the fish community collected in the most pristine mangrove system exhibited the smallest isotopic niche space. In contrast, the highest niche space was found in the mangrove with hydrological disruption, the broadest functional trophic diversity, and lowest trophic redundancy (López-Rasgado et al., 2016). This result coincides with what was found in tropical mangroves, where the largest fish isotopic niche was also found in the mangrove system with greater intervention in contrast to less impacted systems (Medina-Contreras et al., 2021).

In contrast to most of the studies reviewed in the present paper (Hadwen & Arthington, 2007; Samper-Villarreal et al., 2018; Souza et al., 2018;

Medina-Contreras et al., 2021), the $\delta^{15}N$ isotopic values found in fish tissues from highly impacted mangroves exhibited relatively low nitrogen isotope ratios compared with those from the less impacted mangroves. $\delta^{15}N$ values reflect only the input of fixed nitrogen into the system, which is consistent with the presence of cyanobacteria. According to the authors (López-Rasgado et al., 2016), hydrologic restrictions between mangrove systems and the ocean lead to the decline in the abundance of flora (macroalgae) that provide important habitat for marine fauna and alters the dynamics of prey populations, larvae, and juveniles. The lower structural diversity of the fish community sampled in the hydrologically disrupted mangrove was associated with a broader isotopic niche space and less trophic redundancy (López-Rasgado et al., 2016).

Finally, the authors (López-Rasgado et al., 2016) concluded that anthropogenic degradation of mangrove habitat generates fundamental changes in food web structure. The anthropogenic activities that impact fish habitat quality and their functional trophic diversity in mangroves should be assessed using stable isotopes. These markers may also be useful for monitoring ecological recovery after habitat restoration (López-Rasgado et al., 2016).

Aquaculture ponds

Coastal aquaculture expansion resulted in mangrove area loss and ecosystem degradation in past decades. But, what about its effects on mangrove food web structure and function? The use of stable isotopes to evaluate the effects of aquaculture ponds on mangrove food webs is analyzed in this opinion paper through two research papers: one from Tanzania (Mwandya, 2019) and one from China (Herbeck et al., 2021). In the study carried out in China, the effects of aquaculture ponds were evaluated in different sections of an estuarine system. Mangroves were mostly associated to the river and inner estuary, where in general higher ^{15}N values were found in comparison to those of the outer estuary where the authors suggest that the effect of aquaculture nitrogen discharges is less detectable (Herbeck et al., 2021). However, ^{15}N is significantly higher in all areas of the estuary, but the highest increase was found between the river site and the inner bay. In general, $\delta^{15}N$ values of all trophic levels were strikingly high and located at the higher end of the worldwide range for estuaries, indicating that the aquaculture-derived nitrogen is then transferred through the entire planktonic and benthic estuarine food web (Herbeck et al., 2021). Authors finally concluded that $\delta^{15}N$ is a useful indicator to assess the cumulative effects of aquaculture sewage on a mangrove–estuarine food web scale.

The Tanzania study does not specify the effects of aquaculture ponds on the food web studied, since the work focused on the effect of deforestation. However, the authors reported a dietary shift related to a change in the availability of food sources due to mangrove creek disturbance (see Timber harvesting and deforestation section). This evident impact on the mangroves' trophic dynamics is exacerbated by the change of land use to aquaculture ponds, indicating that a combination of mangrove deforestation and construction of fish farms negatively affects fish assemblages and functional groups. Moreover, the recovery of mangrove food web attributes is less likely when these two human activities are combined.

Urban development

The effects of urban development on mangrove food webs were evaluated through the study of juvenile penaeid shrimp abundance and their dietary dependence (mangrove plant-based pathways vs. marine pathways) in two locations (mangrove and a non-mangrove pools) adjacent to an urban development using stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) (Sheaves et al., 2007). Urban development in these areas is generally associated to harvesting of fish and shrimp, regular grass fires, and the development of an extensive trail network. Based on the abundance results, this paper concluded that although situated in a highly urbanized area, the wetland under study provides an important habitat for juvenile penaeid shrimps, including 5 commercial penaeids species, highlighting the functionality of mangroves, even those that are highly impacted by human activities. Based on $\delta^{13}C$ values both marine and wetland primary producers were important to the nutrition of juvenile shrimps. The substantial differences in nitrogen sources in the study pools indicated by different $\delta^{15}N$ values may be signs of increasing anthropogenic nutrient inputs. This paper provides an initial step for the assessment of the ecological value of urbanized tropical coastal littoral wetlands as habitats of juvenile commercial penaeid shrimps and highlights their increasing value.

Conclusion

Based on the results of the studies reviewed in this article and the conclusions given by the authors, stable isotopes are useful tools to address research that aims to evaluate the effect of different anthropogenic activities on the structure and function of mangrove food webs.

Anthropogenic influences on nutrient inputs into mangrove creeks and estuaries, specifically the elevation of nitrogen levels, could potentially alter the structure and function of mangrove food webs. The nitrogen isotope ($\delta^{15}N$) analysis has emerged as an effective way of exploring the uptake of anthropogenic N in mangrove ecosystems. According to the papers reviewed here, it was useful in identifying systems subject to contamination by sewage discharges, in some cases enriching the nitrogen isotopic signal in various constituents of the food web and along the different trophic levels and in other cases only at the level of primary producers. Furthermore, the identification of nutrient enrichment is needed for the management of mangrove systems. Its identification along the food web can assist in the evaluation of the ecological responses to anthropogenic sources of nutrients. The use of sessile invertebrates and fish species with a small home range could be more suitable to study this topic, combining isotopic measurements ($\delta^{15}N$) with traditional nutrient and water transparency measurements.

The results of the studies analyzed suggest that the natural hydrology of mangrove systems could determine if anthropogenic nitrogen will be assimilated throughout the food web or only at a primary producers' level. As demonstrated in the reviewed research, mangrove systems with naturally restricted water circulation are more susceptible to the incorporation of anthropogenic nitrogen along all the constituents of their food webs, evidenced by the enriched values of ^{15} N in their tissues. It is also important to consider the natural abundance of the nitrogen isotope in a system with pristine conditions, which is why researchers compare systems affected by sewage discharges with similar systems that have not been affected by sewage discharges. This is because nitrogen baselines vary depending on the environmental characteristics of each mangrove system. It is important to clarify that although several studies use $\delta^{15}N$ as a tool to evaluate water quality, few studies have investigated the uptake and assimilation of ^{15} N-enriched sewage effluents through the entire food web.

A direct proportional strong relationship between the biomagnification of toxic trace elements (Cr, As, Cd, and Pb) from sewage discharges via land and sea human activities and $\delta^{15}N$ was identified in one of the reviewed studies. For further evidence, more studies are required, as well as the comparison with sites not impacted by wastewater discharges. However, it indicates to another potential variable of which $\delta^{15}N$ could be a useful marker.

Not in all cases, mangroves highly affected by anthropogenic activities will exhibit enrichment of ^{15} N in the tissues of food web constituents. For example, in the study that evaluated the effect of hydrological disruption on mangrove food webs, a decrease in $\delta^{15}N$ was evidenced due to the restriction of water flow, because the predominant primary producers were autochthonous and corresponded mainly to cyanobacteria. It is important to consider that there are mangrove systems naturally enriched or depleted in ^{15} N, therefore this condition as well as the composition of predominant primary producers will determine $\delta^{15}N$ baseline values in case of a hydrological disruption. Also, in another study that evaluated the effect of deforestation, individuals of *Mugil cephalus* collected from deforested mangrove sites had significantly lower ^{15} N values than those collected in near-pristine mangrove forests, due to a change in diet from omnivore to herbivore. Similarly, lower ^{15} N values in samples of *Gerres oyena* from disturbed creeks suggest a change from a fish diet to a benthos diet. The previous results indicate a dietary shift related to a change in the availability of food sources due to mangrove creeks disturbance.

Isotopic carbon values ($\delta^{13}C$) provide evidence of differential use of basal resources by anthropogenically impacted mangrove consumers and their counterparts. For example, in a mangrove with hydrological disruption, fish tissues were ^{13}C enriched compared with mangroves without hydrological disruption, indicating the consumption of autochthonous sources (cyanobacteria) and without differences between climatic seasons. In tropical mangroves of Colombia, fish tissues from a mangrove system impacted by timber harvesting were ^{13}C enriched compared to those from less impacted systems, due to greater consumption of benthic microalgae. Similarly, in Malaysia, δ^{13}C was an indicator of the gradient of temporal deforestation as mollusk and crustacean tissues were enriched in ^{13}C due to the consumption of benthic microalgae, which proliferate in highly fragmented systems compared to systems less impacted by timber harvesting. Additionally, based on δ^{13}C values, one of the studies concluded that large-scale mangrove forest clearing may impact estuarine food webs, with potential consequences to nearby coastal ecosystems. This conclusion extends the scope of the interpretation of the results obtained with this marker.

The deuterium isotope (δD) presented the contrary pattern with ^{13}C-enriched values in consumers from less fragmented forests. The authors of the papers reviewed agree that the carbon isotope is useful for understanding how anthropogenic activities affect consumption patterns of primary sources by different consumers. These results are useful for the management of resources of fishing importance in mangrove areas impacted by human activities, capable of indicating shifts in food web isotopic signals can also be determined based on the deforestation of the forest.

Concerning the effect of waste from metallurgical activities, Pb isotopic ratios (206Pb/207Pb) were sufficient to identify the origin of metal/metalloid contamination in mangrove food webs. However, this topic requires further investigation. Moreover, one conclusion addressing metallurgical activities is highlighted: a combination of techniques and components could be used as a comprehensive toolkit for the study of mangrove systems affected by anthropogenic pollution (See Souza et al., 2018).

Finally based on their size, most fish (See López-Rasgado et al., 2016; Mwandya, 2019; Medina-Contreras et al., 2021) and shrimps (See Sheaves et al., 2007) caught in the mangrove systems under study were juveniles, regardless of the anthropogenic intervention level. This result suggests that despite the modification of structure patterns and function in mangrove food webs by anthropogenic intervention, their nursery function is still maintained, indicating the high resilience of these ecosystems and highlights the ecological importance of such habitats. Finally, most of the mangrove areas studied in the reviewed papers are important fishing areas, offering food security and livelihood for human local communities. Therefore, impacts on their food web functions and structure endangers their role as a food providers.

Acknowledgements Financial and logistic support for this study have been given by the projects: *Aporte de la diversidad funcional de los ecosistemas de manglar al bienestar humano en las costas Caribe y Pacífico, de Colombia: Una mirada desde el enfoque de los servicios ecosistémicos* (code 71323), from the program *Evaluación comparativa de servicios ecosistémicos proporcionados por diferentes tipos de manglar en Colombia* (code 110685270796) accomplished by Universidad del Valle and co-funded by Ministerio de Ciencia Tecnología e Inno- vación through the call number: 852-2019. And the projects: *Variabilidad espacio-temporal del nitrógeno utilizando bioindicadores y nutrientes en ambientes mari- nos transicionales* (codes SIP 20195113, 20200708), *Influencia de los Arribazones de Sargassum spp. como fuente de Nitrógeno en la costa de Caribe Mexicano* (code SIP 20210421). Project SIP 20221362, *Resilience of the Mexican Fish Sector to the Effects of the Covid-19 Pandemic*, CICIMAR. DMC and FA were supported by a doctoral scholarship funded by Consejo Nacional de Ciencia y Tecnología (CONACYT) México and ''Beca de estímulo Institucional de Formación de Investigadores BEIFI'' fellowship from Instituto Politécnico Nacional, México. The author gratefully acknowledge the very valuable help of Zenia Perez Falls for mapping the study areas. In dedication to DMC father's memory.

Funding This study was supported by Ministerio de Ciencia Tecnología e Innovación (Project: Aporte a la diversidad funcional de los ecosistemas de manglar al bienestar humano en las costas Caribe y Pacífico de Colombia: Una mirada a los Servicios Ecosistémicos, Grant No. 71323) from the program: "Evaluación comparativa de los servicios ecosistémicos proporcionados por diferentes tipos de manglar en Colombia" Code. 110685270796, Instituto Politécnico Nacional Projects 20210421-SIP, 20195113-SIP, 20200708-SIP (Grant No. BEIFI 2022) and CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA (CONACYT) (Grant No. 734084, DMC DOCTORAL SCHOLARSHIP and CUV No. 1031683, FA Doctoral Scholarship).

Data availability Manuscript does not have original data.

Declarations

Conflict of interest This paper does not present social, political, or economic conflicts of interests. The Opinion paper does not have original data.

Ethical approval The manuscript does not involve animal experimentation or human participants.

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