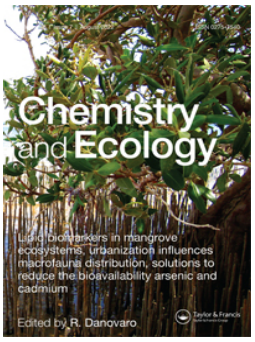

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Assessing variation in below-ground organic matter dynamics in the Ramsar-declared Nylsvley Wetland system, South Africa

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ABSTRACT

Wetlands physical and biological processes are fundamental to the distribution and structuring of organic matter in sediments. This study investigated spatial and temporal changes in organic matter sources in sediments within the Nylsvley Wetland, South Africa across two seasons, five sites and three wetland zones and identified pertinent contributors to sediment organic matter. Results showed distributions were uneven throughout the wetlands, with the seasonal zone having slightly high sediment organic matter in the cool-dry season and the permanent zone had high sediment organic matter in the hot-wet season, whereas the temporary zone had low SOM concentrations. Significant differences in nutrient concentrations were observed across wetland zones and seasons for Phosphorous, Potassium, Calcium and Magnesium, with the seasonal zone tending to be the most nutrient-rich in the cool-dry season, and with permanent zone nutrient levels rising substantially in the hot-wet season. Sediment $\delta^{13}C$ differed significantly among wetland zones, whereas $\delta^{15}N$ was statistically similar. Autochthonous plants were the main sources of organic matter in sediments overall across sites and zones. This study's findings help to better understand the distribution of organic matter in wetland ecosystems and the role wetland zones play in the seasonal provisioning of allochthonous inputs.

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Introduction

Freshwater wetlands are characterised by significant temporal and spatial variations in the pattern and magnitude of water inflows and outflows [1,2]. These produce distinctive water table fluctuations that reflect hydro-meteorological conditions and changes in the predominant water source [1–3]. Wetlands can be characterised by a seasonal hydrological cycle in which water sources comprise precipitation, groundwater, and surface water of different contributions [4–6]. Of the three identifiable wetland zones, the permanent zone is the most efficient at water purification, flood reduction and streamflow regulation [7]. The efficiency of the seasonal zone with regard to organic matter is lower than that of the permanent zone, but still contributes significantly towards water purification.

Sediment organic matter (SOM) is animal and plant detritus, bacteria and/or plankton formed in situ, or derived from a combination of either natural or anthropogenic sources in catchments. The SOM has many functions and is the basis of important biological activity and soil structuring [8,9]. It offers sorption sites for plant nutrients and pollutants and acts as a sink for atmospheric carbon dioxide [10]. All of these functions may be influenced by changes in climate, land use and catchment activities [8,9]. Organic matter in aquatic systems is either produced internally (autochthonous) or delivered from the terrestrial environment (allochthonous) and plays an important role in wetland ecosystem functioning. Terrestrial organic matter (i.e. allochthonous) is increasingly recognised as a strong driver of aquatic ecosystem productivity and is formed outside the ecosystem and then imported through precipitation, dry fall-out, groundwater and lateral transport [11,12]. There is strong evidence that significant transformations of both particulate and dissolved terrestrial organic matter fractions occur in wetland waters, as well as along their transport downstream [13,14]. Sources of organic material in wetlands also depend on the dimensions of the water body and the types of nearby terrestrial communities. In aquatic communities, autochthonous input is provided by the photosynthesis of higher plants and algae in shallow waters, and by microscopic phytoplankton in the photic zone of the entire water body [14,15]. The quantity and quality of organic matter supply and the relative proportion of allochthonous to autochthonous inputs influence food web structure and SOM, as well as determine the potential secondary productivity of wetlands [12,16]. Thus, most of the organic matter that enters wetlands from the watershed (i.e. allochthonous organic matter) or is produced within the wetland (i.e. autochthonous organic matter) is ultimately deposited to the wetland bottom and becomes wetland SOM.

Wetlands function as organic matter sinks and are associated with macroelements such as carbon (C), phosphorus (P) and nitrogen (N) [17]. As a result, wetland sediments contain an archive of past environmental conditions and biogeochemical processes, and these systems can be used to assess ecosystem changes through time. Much of the allochthonous material arrives in wetlands as dissolved organic carbon, but this depends on the wetland type. Sediment organic matter accumulation rates have been studied in conjunction with stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analyses to infer past environmental changes in riverine and wetland ecosystems [18,19]. Stable isotopes occur naturally and changes in their distribution and natural abundance in soils and plants can give important information on the functioning and SOM dynamics of wetland ecosystems. Isotopic values are often influenced by environmental and temporal drivers [18–21]. In ecological studies, stable isotope analyses have been successfully applied to reconstruct diet and migration patterns of organisms, identify food web structures and track flows of elements within an ecosystem [22]. Stable isotopes of carbon and nitrogen in organic matter offer an alternative means to detect SOM variation and changes in aquatic ecosystems [23,24]. The ratios of $\delta^{13}C/^{12}C$ and $\delta^{15}N/^{14}N$, mainly defined as $\delta^{13}C$ and $\delta^{15}N$, respectively, have been used to provide insights into the sources, sinks and cycling of carbon and nitrogen in aquatic ecosystems [25–27]. The temporary zone would have likely the most depleted stable isotope signatures, given that the area is dry outside of the hydroperiod, causing the organic matter in this zone to decompose rapidly [26].

Sediment organic matter is fundamental for wetland formation and function; therefore, understanding the distribution of SOM can lead to better understanding of wetland functioning and general community structuring [28]. The current study explored the distribution of soil nutrient and below-ground SOM content throughout the Ramsar-declared Nylsvley Wetland in South Africa across three wetland zones (i.e. temporary, seasonal, permanent) using a combination of classical and modern stable isotope analysis techniques. We hypothesised that (i) the wetland permanent zone would consist of high nutrients and SOM concentrations, with the temporary zone having the lowest concentrations; (ii) that upper reach sites would have the lowest nutrient and SOM concentrations as they are narrower than the lower reach sites, which have more optimal depositional characteristics; and (iii) allochthonous organic matter sources will be the major contributors to SOM.

Materials and methods

Study area

The study was carried out in Nylsvley Nature Reserve wetland area (24°39′50.0 S, 28° 39′54.4 E) in the upper-reaches of the Mogalakwena River (Figure 1). Nylsvley Nature Reserve forms part of the largest floodplain system in South Africa, covering a total area of 24 250 ha [29]. The reserve lies at an altitude of 1080–1155 m above sea-level, and receives an average of 648 mm of rain per annum, with 85% of the annual rainfall between November and April. Summers are warm to hot (maximum temperature 39° C), while winters are cool to mild (minimum temperature 5.7°C) [30]. The geology of Nylsvley region consists of igneous, sedimentary and metamorphic rocks; however, it is mostly dominated by Waterberg Group sedimentary rocks consisting of conglomerate, sandstone, shale and siltstone [31]. Nylsvley soils consist of the Springbokvlakte Thornveld.

The Nylsvley area is naturally exposed to seasonal flooding and water level fluctuation [32]. The reserve consists of the Central Bushveld vegetation units of the Savanna Biome and a Freshwater Wetland vegetation unit (alluvium vegetation) of Inland Azonal Vegetation. The Nylsvley floodplain Wetland (henceforth referred to as Nylsvley Wetland) plays an important role in supporting regional biodiversity. The wetland flora is made up of an intricate complex of aquatic macrophytes, marginal reed beds and grasslands, ephemeral herblands and riverine thickets.

The study was designed around the collection of 100 sediment samples across sampling sites (N1–N5), 50 sampled in each of two seasons (cool-dry (12–15 June 2019), hot-wet (20–23 March 2020)) for SOM determination, with stable isotope analysis

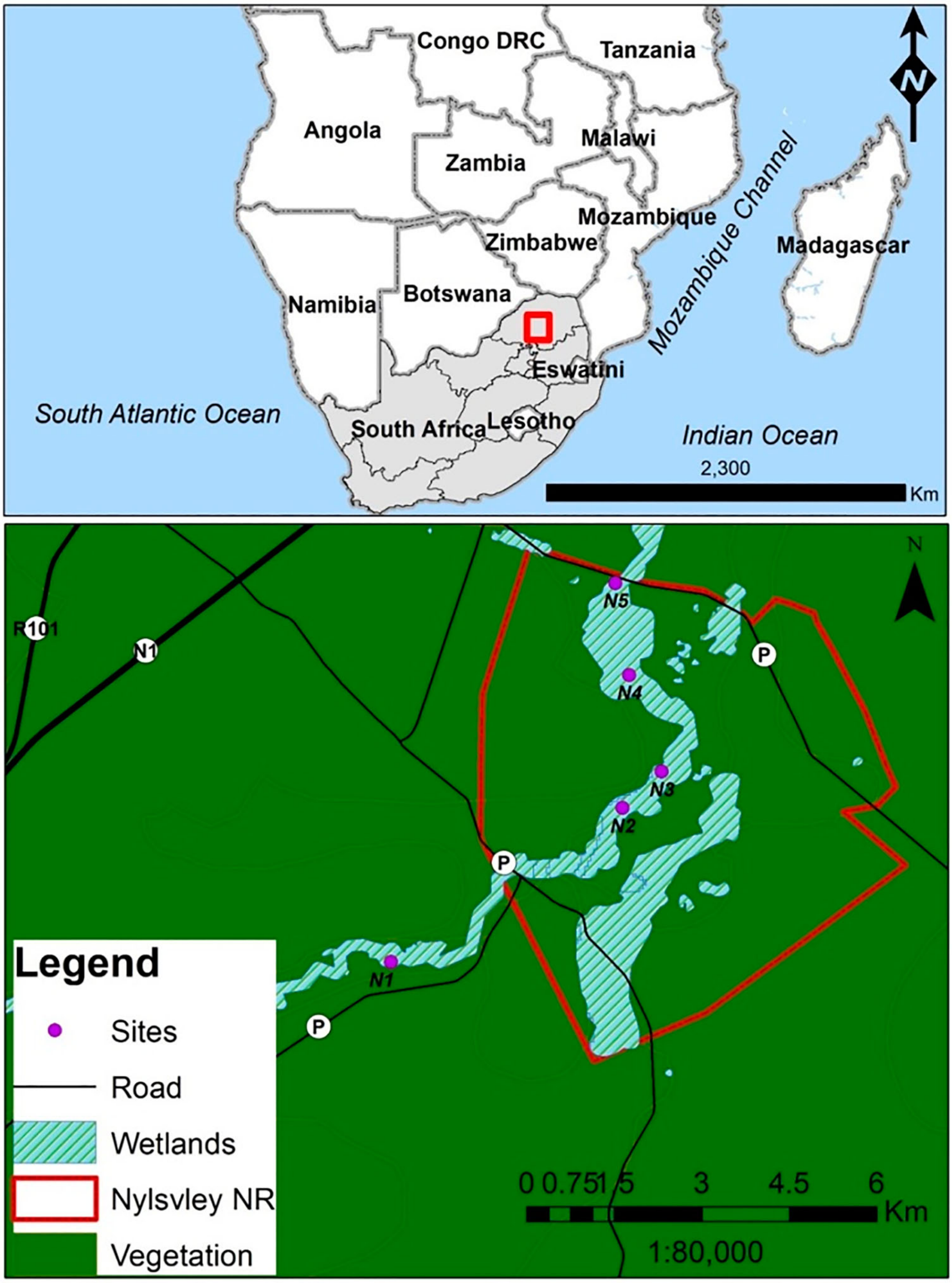

Figure 1. Location of the study sites within the Ramsar-declared Nylsvley Wetland, located in the Limpopo Province of South Africa.

additionally conducted in the cool-dry season. For each sampling site per season, two transects were used across different wetland zones (Figure 2). This resulted in four sampling points being sampled along the temporary zone (i.e. two each on either side of the seasonal zone), four along the seasonal zone (i.e. two each on either side of the

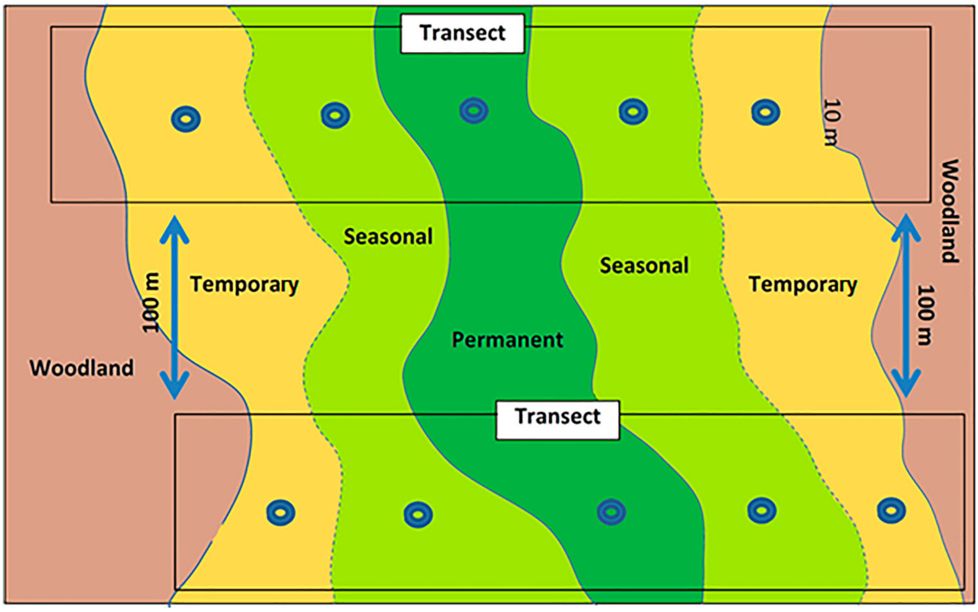

Figure 2. A schematic highlighting the location of the two transects per sampling site within the Ramsar-declared Nylsvley Wetland (source: [33]).

permanent zone) and two along the permanent zone per site (i.e. $n = 10$) (Figure 2). Sediment samples, together with particulate organic matter (POM), fish, plants, invertebrates and senescent leaves/detritus as sources of organic matter, were collected from the three wetland zones: (1) permanent (2) seasonal and (3) temporary, for SOM and stable isotope value determination.

Sampling

Sediment samples were collected for both seasons to determine SOM and nutrient content, whereas isotope samples (i.e. plants, invertebrates, vertebrates) were collected once during the cool-dry season.

Sediment

A total of only 90 sediment samples was collected instead of 100 between both seasons, because of the presence of hippos at site 1 during the hot-wet season, making it impossible to safely sample this site. For each season, site and wetland zone, sediment samples ($n = 2$) of approximately 1.5 kg were collected for SOM, nutrient and isotope analysis using a hand auger (diameter 12 cm) up to a 10 cm maximum depth, and placed in labelled polyethylene ziplock bags (see Dalu et al. [33,34] for methods).

Phytoplankton and plants

All available plant species ($n = 4$) per site and wetland zone were collected for stable isotope determination in the cool-dry season. Phytoplankton was sampled using a 20 µm plankton net (diameter 30 cm) and decanted into 250 mL polyethylene containers, where it was vacuum filtered onto GF/F filters to concentrate the samples. Emergent plant materials were collected by hand into labelled ziplock bags before being placed on ice. The plant leaves collected were milkweed *Gomphocarpus physocarpus*, common reed *Phragmites australis*, knotweed *Persicaria* spp., lantana/shrub verbena *Lantana camara,* Pangola-grass *Digitaria eriantha*, Guinea grass *Panicum maximum*, black-jack *Bidens pilosa*, Bermuda grass *Cynodon dactylon*, sedge *Cyperus* spp., seed thrower *Sporobolus* spp. and water primrose *Ludwigia Stolonifera.* All the plants were autochthonous, with the exception of *L. camara*, *D. eriantha*, *P. maximum*, *C. dactylon* and *B. pilosa*.

Invertebrates and vertebrates

Macroinvertebrates were sampled using a Nylon mesh (500 µm size) with an aluminium rim that allowed a sampling distance of 1.5 m. A 10 m transect was sampled by submerging the net and sweeping the demarcated area for 5 min. Fish were sampled along a 5 m length using a SAMUS-725G backpack electrofisher from all different habitat biotopes (i.e. pools, marginal vegetation) (see Dalu et al. [32] for detailed methods). All fish were identified to species level according to Skelton [35] and fin clip samples were taken from representative fish species ($n = 5–10$). All samples ($n = 4$) were placed on ice in labelled containers before further processing in the laboratory.

Nutrient analysis

Prior to sending the samples for analysis, the sediment was oven and dried at 60°C for 48–72 h. Subsamples (i.e. 200 g) of dried sediments were labelled according to seasons, zones and sites, and sent for analysis at BEMLAB in Cape Town, a South African National Accreditation System (SANAS) certified laboratory for analysis of phosphates (P), potassium (K), calcium (Ca) and magnesium (Mg) (see Dalu et al. [33,34] for methods). Sediment P concentration was analysed using a Bray-2 extract method, whereas, cation elements (K, Ca, Mg) were fixed with a 2:2 mixture of 2 N nitric acid (HNO_3) and hydrochloric acid at 90°C for 35 min. The cation elements from the extracts were then determined using an ICP-OES optical emission spectrometer (Varian, Mulgrave, Australia).

Sediment organic matter analysis

Sediment organic matter (SOM) was measured to estimate the amount of organic matter present from the three wetland zones for each site and season. To determine SOM, approximately 3 g dry mass of homogenised sediment sample from each wetland zone, site and season was measured and burnt at 450°C in a furnace for 16 h. After combusting the sediments, the samples were weighed again using the loss in ignition (LOI) method and the difference in weight was used to calculate the percentage organic matter composition [36,37].

Stable isotope analysis

All samples (i.e. sediments, plants, invertebrates, vertebrates) from the cool-dry season were oven dried (60°C, 72 h) in aluminium foil envelopes, and each crushed to a fine homogeneous powder using a mortar and pestle. Whole organisms for invertebrates (i.e. shells were removed for mollusc groups such as snails, while muscle tissue was used in crustaceans) and fin clips for vertebrates were ground to powder for each site and zone. For filtered samples, approximately 0.5 mg of material was scraped off from the dry filters and placed into tin capsules, whereas, for all other materials, subsamples were weighed to approximately 1 mg into tin capsules. Sediment samples (~3 g) were treated to remove carbonates using 1 N HCl based on the drop-by-drop technique by Jacob et al. [38] until bubbling stopped, before being rinsed with distilled water and dried at 60°C. Since the sediment acid treatment can potentially alter the sediment stable ^{15}N values, we did not include these values for SOM during statistical analyses (see Ryba and Burgess [39] for further details).

All samples were analysed for stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes at the University of Pretoria Stable Isotope Laboratory using a Flash EA 112 Series coupled to a Delta V Plus stable light isotope ratio mass spectromoter via a ConFlo IV system (Thermo Fischer, Bremen). The standards used were referenced to atmospheric nitrogen and Vienna Pee-Dee Belenmite for $\delta^{15}N$ and $\delta^{13}C$, respectively. Standard delta notation (δ) was used to express stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), with the isotope ratios being expressed in parts per thousand (‰) with the differences from a standard reference material:

$$\delta^{13}\mathrm{C or} \delta^{15}\mathrm{N} = \left[\left(\frac{R_{\mathrm{sample}}}{R_{\mathrm{standard}}} - 1\right)\right] \times 1000$$

where $R = {}^{15}N/{}^{14}N$ or ${}^{13}C/{}^{12}C$, respectively [22,40].

Data analysis

Differences in SOM and stable isotopes (C, N) among wetland zones (temporary, seasonal, permanent), sites (N1–N5) and seasons (cool-dry, hot-wet; in the case of SOM only) were tested using a two-way ANOVA after the data was found to meet all the parametric tests i.e. homogeneity of variances and normality. Pairwise comparisons were done for significant variables to assess differences among wetland zones and sites using Tukey's post-hoc analysis. These tests were performed using Statistica version 7 (StatSoft, Tulsa, OK).

A Kruskal–Wallis analysis was conducted to assess differences in $\delta^{13}C$ and $\delta^{15}N$ values across wetland zones and sites, with Mann–Whitney pairwise comparisons being conducted to assess within zone and site differences using Statistica version 7. Bayesian Stable Isotope Analysis in R (SIAR) was used to assess the relative SOM contributions to the different SOM sources (i.e. plants were divided into allochthonous and autochthonous organic matter; invertebrates and invertebrates were combined into animals) across wetland zones, sites and seasons. The Bayesian model combines variation and uncertainty in parameters with an enrichment factor. Assumptions of small $\delta^{13}C$ and $\delta^{15}N$ fractionation factors were 0.5 for both isotopes based on short-term degradation experiments [41]. Furthermore, a Pearson correlation was conducted to assess the relationship between SOM content and isotope ($\delta^{13}C$ and $\delta^{15}N$) values.

Results

Sediment chemistry

Some of the soil nutrient chemistry data presented here have been partly presented in Dalu et al. [32–34]. Few consistent differences were observed among the wetland zones and sites between seasons (Figure 3). Phosphorus (P) had very low concentration in all wetland zones and sites, with the exception of the permanent zone sites N2, N4 and N5 during the hot-wet season. The potassium (K) concentration was high in the permanent zone in two of the hot-wet season sites and was low in the permanent zone across all sites during the cool-dry season (Figure 3). The permanent zone had low calcium (Ca) and magnesium (Mg) concentrations in all sites during the cool-dry season (Figure 3). The seasonal zone exhibited the highest observed concentrations overall in all sites, although the permanent zone recorded increased concentrations most in the hot-wet season.

Based on ANOVA analysis, all nutrient concentrations across sites were not significantly different, except for K concentration which was significantly different ($F = 4.99$, $p = 0.001$). Furthermore, significant wetland zone differences were observed for P ($F = 13.27$, $p < 0.001$), K ($F = 4.82$, $p = 0.011$), Ca ($F = 21.89$, $p < 0.001$) and Mg ($F = 30.28$, $p < 0.001$), with significant seasonal differences being observed for K ($F = 5.90$, $p = 0.018$), Ca ($F = 27.96$, $p < 0.001$) and Mg ($F = 5.87$, $p = 0.018$). Using pairwise comparisons, significant ($p < 0.05$) site variations were observed for K, Ca and Mg (see Table 1) and wetland zones ($p < 0.05$) for all nutrients with the exception of P (seasonal *vs* temporary, $p = 0.167$) and K (permanent *vs* temporary, $p = 0.423$) (Table 1).

Sediment organic matter content

During the cool-dry season, SOM content varied among the three wetland zones (Figure 4). The mean SOM content was slightly high in the seasonal zone in sites N1

Table 1. Tukey's pairwise comparison results of significant ($p < 0.05$) variables of wetland sites and zones.

Variable	Pair	P
Sites		
K	N1 *vs* N2	0.011
K	N2 *vs* N3	0.017
K	N3 *vs* N5	0.003
K	N5 *vs* N1	0.002
Ca	N1 *vs* N2	0.043
Mg	N1 *vs* N2	0.009
Mg	N2 *vs* N3	0.023
Wetland zones		
P	Permanent *vs* Seasonal	0.002
P	Permanent *vs* Temporary	<0.001
K	Permanent *vs* Seasonal	0.004
K	Seasonal *vs* Temporary	0.036
Ca	Permanent *vs* Seasonal	<0.001
Ca	Seasonal *vs* Temporary	0.042
Ca	Temporary *vs* Permanent	<0.001
Mg	Permanent *vs* Seasonal	<0.001
Mg	Seasonal *vs* Temporary	0.012
Mg	Temporary *vs* Permanent	<0.001

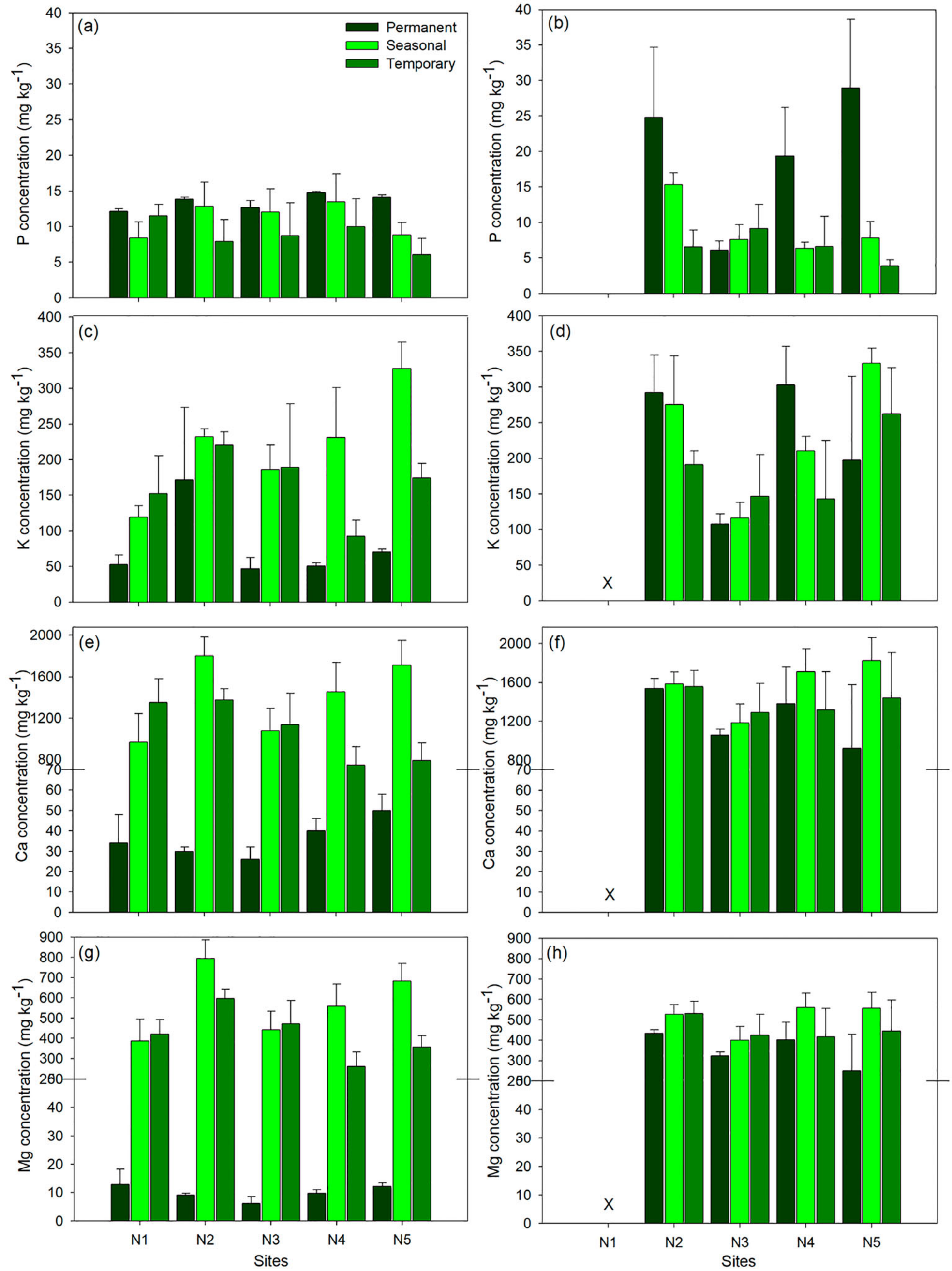

Figure 3. Variation in (a, b) phosphorus (P), (c, d) potassium (K), (e, f) calcium (Ca) and (g, h) magnesium (Mg) concentration between two seasons: (a, c, e, g) cool-dry, and (b, d, f, h) hot-wet seasons in the Nylsvley Wetland across three wetland zones and sites. The 'x' in the hot-wet season indicates no sampling due to lack of access to the site. Means are ± standard deviation.

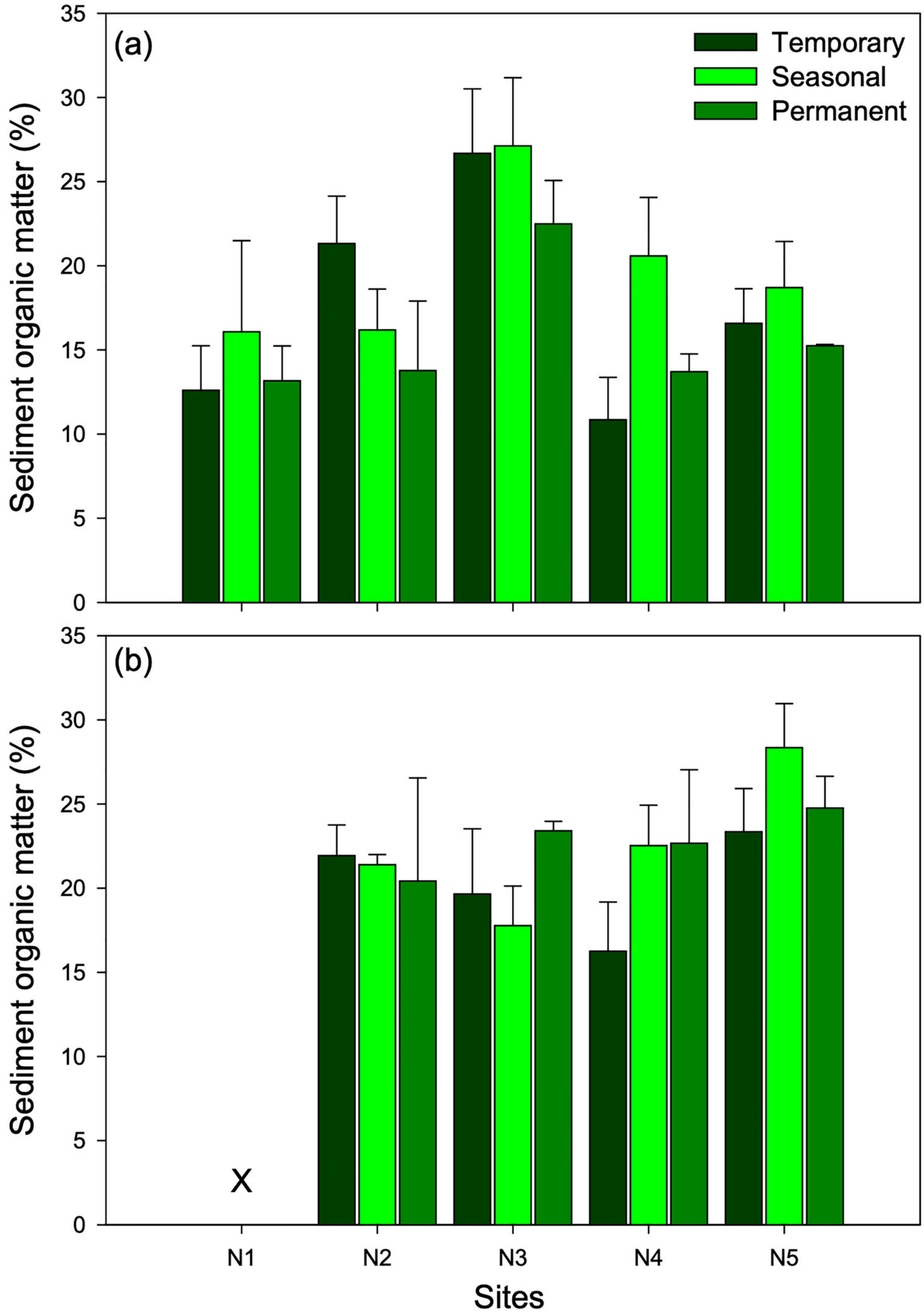

Figure 4. Sediment organic matter concentrations (%) in three wetland zones across 5 sites in Nylsvley Wetland for (a) cool-dry and (b) hot-wet seasons. Means are ± standard error

(16.1 ± 5.4%), N3 (27.1 ± 4.0%), N4 (20.6 ± 3.5%) and N5 (18.7 ± 2.7%) during the cool-dry season (Figure 4). During the hot-wet season, the temporary zone had the lowest SOM content at site N4 (16.3 ± 2.9%), and high SOM content was recorded at site N5 in the seasonal zone (28.3 ± 2.6%). No clear patterns were observed across wetland zones and sites for the two seasons (Figure 4). Significant site ($F = 3.050$, $p = 0.023$) and seasonal ($F = 5.520$, $p = 0.022$) differences were observed, whereas, no significant differences ($F = 1.372$, $p = 0.261$) were observed among wetland zones. Using pairwise comparisons, significant site differences were observed for N1 *vs* N3 ($p = 0.003$) and N1 *vs* N5 ($p = 0.018$).

Stable isotope ratios

The mean stable isotope value fractions are highlighted in Table S1. The sediment mean $\delta^{13}C$ values generally showed an increasing trend for sites N2–N5 for the temporary to permanent zones, whereas site N1 showed a slight opposite trend (Figure 5(a)). The sediment mean $\delta^{13}C$ values ranged from −26.67‰ to −19.53‰ across the three wetlands zones, with the permanent zone having slightly more enriched values (Figure 5(a)). The sediment mean $\delta^{15}N$ values ranged from 0.01‰ to 2.60‰ (Figure 5(b)). However, a decreasing trend was observed for the $\delta^{15}N$ values in sites N1 and N2 and increasing trend for site N4 from the temporary to the permanent zones. Seasonal zones in sites N3 and N5 had depleted and enriched values among wetland sites zones, respectively (Figure 5(b)).

Sediment $\delta^{15}N$ ($H = 5.895$, $df = 4$, $p = 0.207$) and $\delta^{13}C$ ($H = 3.388$, $df = 4$, $p = 0.495$) isotope values were found to be similar across study sites. Sediment $\delta^{15}N$ ($H = 0.263$, $df = 2$, $p = 0.877$) values were found to be non-significant across wetland zones, whereas sediment $\delta^{13}C$ isotopes ($H = 30.977$, $df = 2$, $p < 0.001$) were significantly different across wetland zones. Using Mann Whitney–U test, significant differences were observed for permanent *vs* seasonal ($p = 0.018$), permanent *vs* temporary ($p < 0.001$) and seasonal *vs* temporary ($p < 0.001$).

Strong and negative relationships were observed for sediment $\delta^{15}N$ and SOM values for the seasonal ($r = -0.91$, $p = 0.033$) and permanent ($r = -0.92$, $p = 0.027$) zones, whereas the sediment $\delta^{13}C$ and SOM values were negatively and significantly correlated ($r = -0.81$, $p = 0.016$) within the permanent zone.

The SIAR outputs suggested that in the permanent, seasonal and temporary zones, there were no clear patterns of organic matter source contributions to SOM (Figure 6). The fractions of allochthonous organic matter contribution generally decreased from the temporary to the permanent wetland zone. In site N2, allochthonous organic matter was generally high across all wetland zones, whereas in Site N3, autochthonous organic matter was the dominant contributor to SOM fractions. Animal organic matter contributed the least to SOM in the majority of wetland zones and sites (Figure 6).

Discussion

Our results indicated an uneven distribution of nutrients and SOM throughout the Nylsvley Wetland across zones, sites and seasons. The permanent wetland zone did not consist of highest nutrients and SOM concentrations among most of the wetland zones and sites,

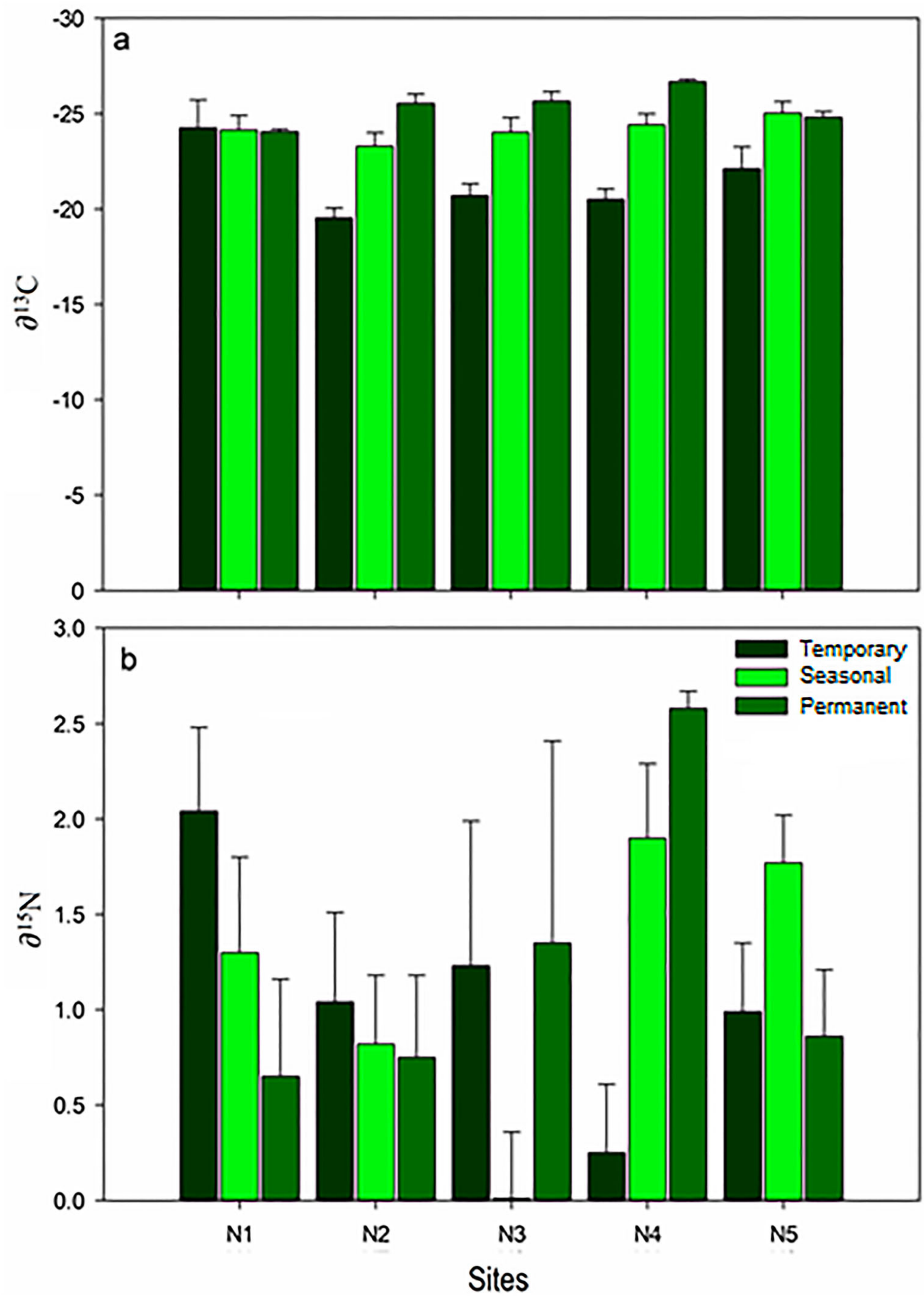

Figure 5. The sediment mean (a) $\delta^{13}C$ and (b) $\delta^{15}N$ values (‰) variation across the wetland zones and study sites in the Nylsvley Wetland. Means are ± standard deviation.

whereas the seasonal zone tended to have highest concentrations. The K, Ca and Mg concentrations were relatively low in the temporary zone during the cool-dry season. Similarly, the upper reach sites did not have low nutrient and SOM concentrations across

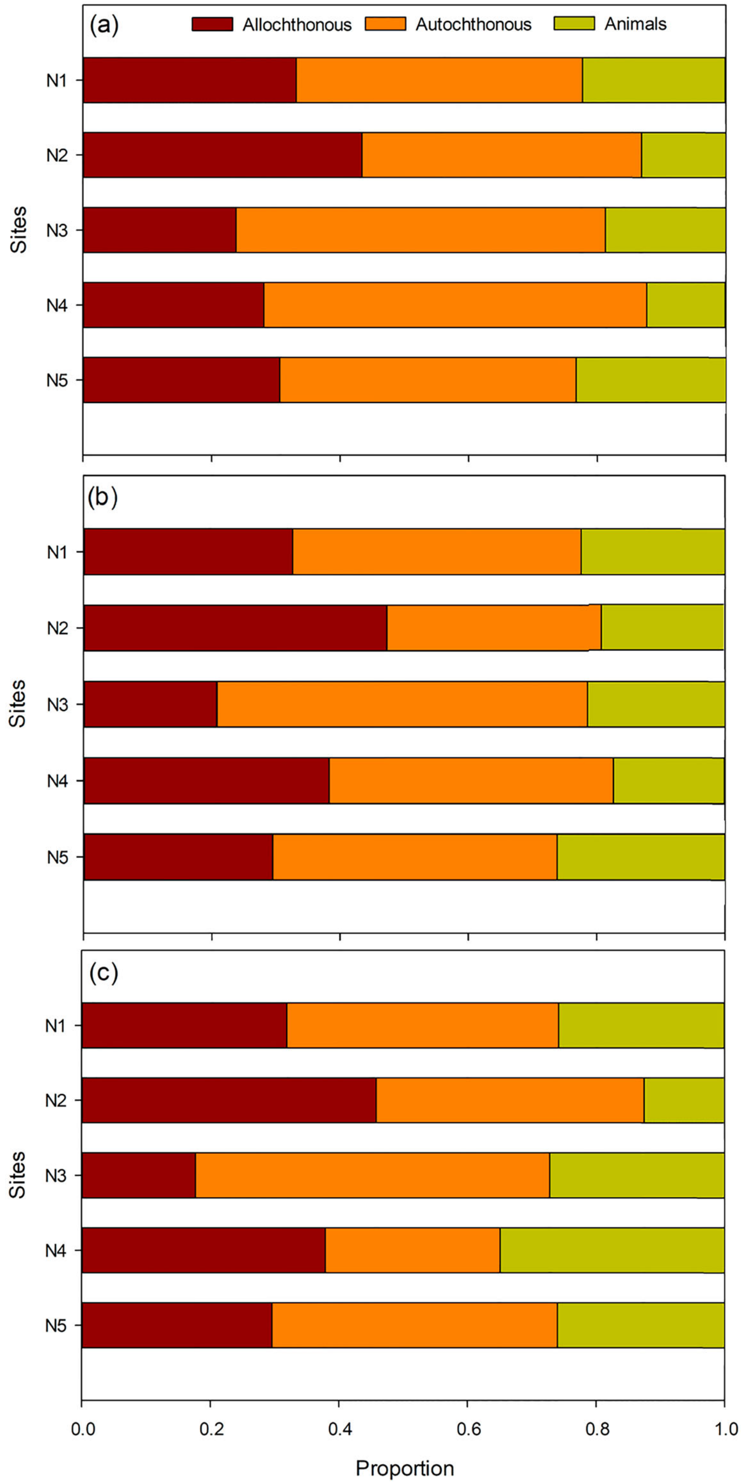

Figure 6. SIAR Proportions (%) of allochthonous, autochthonous and animals' inputs across N1–N5 in the (a) temporary, (b) seasonal and (c) permanent zone.

seasons. Thereby, our first and second hypotheses are rejected. The autochthonous organic matter was found to be a major source contributor to SOM in the temporary wetland zone, whereas lower $\delta^{13}C$ values indicative of the autochthonous organic matter sources were observed in the permanent zone [42], thereby partially confirming our third hypothesis.

Sediment P content increased in most of the permanent zone during the hot-wet season which could be related to surface runoff from the nearby terrestrial environment or increased decomposition rates leading to P leaching, whereas in the temporary zone, the decrease in P concentrations was possibly due to uptake by plants/macrophytes. In the hot-wet season, all nutrients (K, P, Ca, Mg) increased with rainfall. High K, Ca, Mg and P in the hot-wet season could be attributed to increased organic matter decomposition rates. Thus, the increase in OM decomposition will result in the release of nutrients and metals from the OM causing an increase in metal and nutrient content with the system. During the rainy season increased aerobic decomposition is favoured, resulting in increased decomposition [43]. During the cool-dry season, the P concentration in the permanent zone (between 10 and 15 mg kg^{-1}) was higher than in the seasonal and temporary zones. This was because there was no water/rainfall in this period, resulting in drying of the soil and sediments and subsequently less organic matter in the wetland in the seasonal and temporary zones. The seasonal zone had the highest concentration in K, Ca and Mg during the cool-dry season, whilst the permanent zone was the lowest in these three nutrients.

Sediment organic matter in natural wetlands is largely a product of the decomposition of animal and plant residues, including mineralisation and erosion, which are influenced by many biological and non-biological conditions [44]. Abundant biomass, anaerobic conditions, and slow water velocity in wetlands constrain decomposition rates of organic matter in soil and accelerate the accumulation of organic matter [45,46]. This explains the low amount of SOM in the permanent zone in the cool-dry season, which has similar characteristics. The amount of SOM in the seasonal zone was high in both seasons (cool-dry and hot-wet) in sites N3 and N5 (27% and 28%, respectively). The seasonal zone has moderate conditions (temperature, moisture and anaerobic condition), being an intermediary, and this quickens the decomposition rate of organic materials. The variation in SOM might be explained by the differential capacities for SOM holding in wetland soils, as well as different amounts of plant litter inputs including the influence of physical, biological and chemical factors within the five sites in the three wetland zones, and being further influenced by the distance to riverbed, water table and soil moisture [47–49].

The SOM concentration is influenced by multiple other factors. According to Wang et al [46], organic matter at higher elevation decomposes much faster under aerobic conditions than that at low elevation. Moreover, elevation also indirectly affects the production of SOM through vegetation types, microbial processes, and soil physical and chemical properties [50]. Slope gradient may also fundamentally affect the migration of organic matter by controlling water velocity [51]. This further explains the variations along slope topography in the distribution of organic matter across the five wetland sites. The permanent zone, which was at lower elevation compared to others, recorded slightly low SOM content. High elevation in Nylsvley Wetland may cause lager spatial variation across the landscape, which may lead to gradual change of SOM among elevation intervals.

The vegetation composition varied greatly along the Nylsvley floodplain. Differences in vegetation composition were observed across five sites. Sites N2, N3 and N5, which had great abundance of vegetation, were composed of high organic matter. Plant litter inputs could have been the major source of organic matter of the soil surface, due to harvesting of *Phragmites australis.* The litter could have been carried to the areas far from the riverbed by floodwater, becoming difficult to decompose under inundation or drought conditions [52], for example, *Phragmites australis* and *Triarrhena* sp. stubbles take longer to return to soil, having more complex structures (lignin and cellulose), which are often harder to degrade than those of *Carex* and *Phalaris* [52].

The concentration of organic matter in soil was slightly higher in the hot-wet than in the cool-dry season in this study. The higher the temperature, the more favourable the conditions for the development of microorganisms, which increases the microbiological activity of soils. Kalbitz et al. [53] claim that changes in the dissolved organic matter content in soils are also due to the amount and dynamics of precipitation. Soils in wetter and cooler climates generally contain more organic matter than soils in drier climates. The two seasons (hot-wet and cool-dry) have different climates, air temperatures and water levels. During the cool-dry season, wetlands are almost dry and some are completely dry since there is no rain, whilst in the hot-wet season wetlands are full of water because of rainfall events. Consequently, there is less organic matter during the dry season due to less water being available in the wetlands, resulting in fewer animals/plants being found growing in the wetland.

Previous studies suggested that measurement of ecosystem (plant and soil) stable isotopic compositions ($\delta^{13}C$ and $\delta^{15}N$) can provide insight into soil C and N cycling [54,55]. Spatial and temporal variations in the sources of organic matter deposited within the Nylsvley wetland were clearly represented by stable isotope signatures. We found low $\delta^{13}C$ signatures in sediments in the temporary zone at most sites. It was hypothesised that the lower reach sites would be more autochthonous as they were shallow and slow flowing with increased potential for primary productivity. A possible explanation for this trend was the influence of wetland water in the temporary zone, where carbon sources with low $\delta^{13}C$ signatures, such as terrestrial matter and phytoplankton, dominated (ranging from −26.67‰ to −19.53‰). The findings further suggest that $\delta^{15}N$ signature values varied greatly in all wetland sites: in N1, the temporary zone was the highest; in site N4 the permanent zone was higher than in the temporary site; and in site N5 the seasonal zone was enriched compared to the other two wetland zones.

Nitrogen presents unique challenges due to its chemical versatility, and the amount of Nitrogen accumulated in wetland soils depends on the balance between plant production and decomposition, and the balance between allochthonous import and particulate export. Most soils have $\delta^{15}N$ values of 2‰ to 5‰. On a regional and global scale, soil and plant $\delta^{15}N$ values systematically decrease with increasing mean annual precipitation and decreasing mean annual temperature [56]. Nitrogen from human and animal waste is enriched with $\delta^{15}N$ [57]. Enriched $\delta^{15}N$ of various taxa has been used as an indicator for organic matter influence in the freshwater wetland environment [58]. However, further studies are required to assess the link that exist between isotopes, and carbon and nitrogen cycles. Stable isotope nitrogen values were low, ranging from 0.5 ± 0.5‰ to 10.3 ± 0.3‰. The $\delta^{15}N$ values varied, but reached a maximum in the permanent zone in site N4, then remaining high and stable.

Conclusions

Allochthonous organic matter sources derived from plant materials influence sediments (second highest after autochthonous here), because biotic and abiotic characteristics such as changes of freshwater discharge and sources of organic matter all influence stable isotope (SI) composition of sediments. This study demonstrated that autochthonous input (plants and animals) was the main source of organic matter in all three wetland zones: permanent, seasonal and temporary. However, there was some variation among sites where allochthonous was the main source, specifically, in sites N2 and N4 in the permanent zone. The SIAR proportions indicated that animals also had an input; being a source of organic matter, although minimally compared to autochthonous and allochthonous sources. The seasonal hydroperiod may help explain the relatively high productivity of organic matter in the Nylsvley Wetlands. Further studies should also focus on integrating the effect of grain size on SOM patterns and distribution.

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Ethical approval

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