Aquatic macroinvertebrates associated with Salvinia molesta according to developmental stage in two tropical lagoons (Ono and Hébé, Côte d’Ivoire)

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Research Article

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Abstract

This study investigated macroinvertebrate communities associated with different growth stages of *Salvinia molesta* in Ono and Hébé lagoons by describing their structure and functional traits, and examining how environmental factors influence faunal composition. Monthly samples were collected using a dip net, and key abiotic parameters were recorded. Although environmental variables varied between lagoons, pH remained stable. A total of 144 taxa belonging to 49 families, 13 orders, and five classes were identified, including 77 in Ono and 101 in Hébé. The reduced diversity in Ono is strongly linked to local anthropogenic disturbances. In both lagoons, taxon richness increased from juvenile to adult fern stages, with Insects, especially Coleoptera, Odonata, Heteroptera, and Diptera, dominating the communities. The highest values of rarefied richness, Shannon-Weaver index, and density appeared at the adult stage, indicating greater structural complexity. Predators constituted the main trophic group, while harmful taxa were approximately twice as abundant in adult stands. Conductivity, pH, dissolved oxygen, temperature, transparency, nitrate, and phosphorus were the main drivers of macroinvertebrate distribution. Sensitive indicator taxa (Ephemeroptera and Trichoptera) were more abundant and consistently recorded in Hébé, unlike in Ono, further highlighting the negative impact of anthropogenic pressures on this lagoon.

Introduction

Native to South America, *Salvinia molesta* started invading inland water bodies in several African countries in the early 1980s. It is a free-floating aquatic fern that lives in freshwater environments (Labrada and Fornasari, 2002). The introduction of such non-native aquatic plants impacts environmental conditions and the health of freshwater ecosystems. Its proliferation can greatly alter the structure and dynamics of biotic communities, including sessile algae, zooplankton, phytoplankton, and invertebrates such as many insect larvae, mollusks, crustaceans, and juvenile and adult fishes (Ohtaka et al., 2011). Aquatic macroinvertebrates associated with macrophytes play a vital role in freshwater wetlands, supporting numerous important ecological processes (Wu et al., 2019). They are crucial to ecosystem function and act as a key link in transferring energy from primary production to higher trophic levels in the food web (Wahl et al., 2021). As a result, they serve as a significant food source, providing essential nutrients like protein and calcium necessary for species at higher trophic levels, including fish and waterfowl (Kangle et al., 2021). Several studies have examined macroinvertebrate communities associated with *Salvinia molesta* in freshwater ecosystems (Mfundisi et al., 2008; Ohtaka et al., 2011; Motitsoe et al., 2020; Wahl et al., 2021). Surprisingly, no research has documented how the developmental stages of this macrophyte influence macroinvertebrate communities, despite the presence of two distinct physiological stages observable in the water fern in the Ono and Hébé Lagoons. Therefore, it is scientifically important and valuable for managing fish, waterfowl, and other organisms at higher trophic levels to identify the factors affecting the distribution of epiphytic macroinvertebrates within and between these two developmental stages of *Salvinia molesta*, along with the ecological conditions of the Ono and Hébé lagoons, to enhance ecosystem management.

Materials and methods

Study area

Ono lagoon is located 12 km from Bonoua and covers approximately 481 hectares, of which 162 hectares are exploitable. It is fed by the Wamon and Amian rivers and is connected to the Atlantic Ocean via the Comoé River and the Ebrié lagoon. Hébé lagoon, located 9 km southeast of Bonoua, covers 244 hectares. Its shores are swampy, and it features a completely open water surface. Hébé lagoon is fed by the Hébé and Motobé rivers and connects to the Kodjoboué lagoon during flood periods (Fig. 1).

Data collection and laboratory procedure

Sampling was carried out from August 2015 to September 2016. *Salvinia molesta* was collected using a 0.053 m^2 net with a 500 μm mesh. Plant material and associated macroinvertebrates were washed and filtered through a 0.2 mm sieve. Afterwards, the samples were preserved in a 10% formaldehyde solution in labeled polyethylene bottles. In the laboratory, the preserved samples were rinsed through a 500 μm mesh sieve to remove formaldehyde and collect all macroinvertebrates. These were then fixed in a 70% alcohol solution for identification. Plants were drained of excess water, weighed to estimate wet biomass, and dried at 105°C for 2 days to determine dry weight. Macroinvertebrates were identified to the lowest taxonomic level possible using references such as Déjoux et al. (1981), De Moor et al. (2003a; b), and Tachet et al. (2010). After identification, each taxon was assigned to a functional feeding group based on its trophic category, following Merritt and Cummins (1996) for insects and Pointier et al. (1989) for mollusks.

Measurement of environmental variables

Alongside the biological examinations, we also carried out several physical and chemical analyses. Every month, between 8:00 am and 10:00 am at each sampling site, we measured temperature, transparency, pH, conductivity, and dissolved oxygen. We gathered water samples in 500 mL polyethylene bottles, which we kept below 4°C and transported to the laboratory. In the laboratory, dissolved inorganic nutrients such as nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) were analyzed using a HACH DR 6000 spectrophotometer.

Data analysis

The macroinvertebrate density was determined as the total number of individuals (N) per 100 g dry weight (d.w.) of macrophytes. Invertebrate diversity was quantified using the Shannon-Weaver diversity index and Pielou evenness. To allow fair comparisons of taxonomic richness across samples with differing abundances, rarefaction of total taxa for each stage was conducted by randomly drawing a specified number of individuals from each sample, as described by Magurran (2004). Before performing comparison analyses, data normality was tested using the Shapiro-Wilk test. Since the distribution of biotic and abiotic data was not normal ($P < 0.05$), the Kruskal-Wallis non-parametric test was performed to compare data between developmental stages. If the Kruskal-Wallis test indicated significant differences, the Mann-Whitney U test was subsequently used for pairwise comparisons. The significance level was set at $p = 0.05$. All analyses were performed using the R package. The frequency of occurrence (FO) was calculated using the formula: $FO = (Ni / Nts) \times 100$, where Ni represents the number of samples containing species i, and Nts is the total number of samples collected. The frequency of occurrence (FO) was used to classify species according to Albertoni et al. (2007): very frequent ($F \geq 70\%$); frequent ($40\% \leq F < 70\%$); low frequent ($10\% \leq F < 40\%$); sporadic ($F < 10\%$). Redundancy Analysis (RDA) assessed relationships between macroinvertebrate distribution and environmental variables. Statistical significance of variables and axes was determined using the Monte Carlo permutation test.

Results and Discussion

Environmental variables

The median values of environmental variables are summarized in Table 1. Temperatures ranged from 25.58°C (Ono) to 31.93°C (Hébé), reflecting similar patterns seen in dissolved oxygen, pH, and conductivity. The extreme pH varied from 5.43 (Ono) to 8.33 (Hébé), while dissolved oxygen ranged from 1.08 mg/L (Ono) to 7.27 mg/L (Hébé). Conductivity varied from 6.33 µS/cm (Ono) to 57.66 µS/cm (Hébé). Except for pH, temperature, dissolved oxygen, and conductivity were significantly higher in Hébé (Mann-Whitney, $p < 0.05$). Water transparency extremes (2.23 m and 0.42 m) were recorded in Ono and Hébé, respectively, with median values significantly higher in Ono lagoon (Mann-Whitney test, $p < 0.05$). Nutrient levels were higher in Ono (Mann-Whitney test, $p < 0{,}05$), with nitrate ranging from 0.74 mg/L (Hébé) to 4.87 mg/L (Ono), and orthophosphate from 0.05 mg/L (Hébé) to 0.9 mg/L (Ono).

Table 1
Inter-lagoon variations (median, minimum, and maximum) of environmental parameters measured in the Ono and Hébé lagoons. Values followed by different letters are significantly different ($p < 0.05$).

Parameters	Ono	Hébé
Temperature (°C)	26.88 ^{a} (25.58–29.32)	30.03 ^{b} (27.6–31.93)
Dissolved oxygen (mg/L)	1.93 ^{a} (1.08–5.44)	6.19 ^{b} (4.67–7.27)
Conductivity (µS/cm)	19.11 ^{a} (6.33–25.22)	37.83 ^{b} (9.78–57.66)
pH	6.11 ^{a} (5.43–7.53)	6.5 ^{a} (5.65–8.33)
Transparency (m)	1.57 ^{b} (0.86–2.23)	0.71 ^{a} (0.42–0.92)
Nitrate (mg/L)	2.89 ^{b} (2.07–4.87)	1.81 ^{a} (0.74–2.51)
Orthophosphate (mg/L)	0.43 ^{b} (0.15–0.9)	0.25 ^{a} (0.05–0.49)

Macroinvertebrate community composition and diversity

A total of 144 taxa belonging to 49 families, 13 orders, and five classes, with 77 recorded in Ono and 101 in Hébé (Table 2). In the Ono lagoon, 55 taxa were common to both life stages, compared to 72 in Hébé. Taxa richness increased from the juvenile to the adult stage of *S. molesta*, with 59 to 73 taxa recorded in Ono and 76 to 97 in Hébé, respectively. In Ono, insects dominated (70 of 77 taxa; 90.91%), mainly Coleoptera (31.17%), Odonata (29.87%), and Heteroptera (16.88%), and two families were prevalent (Dytiscidae and Libellulidae). In Hébé, insects also prevailed (86 of 101 taxa; 85.15%), with Diptera (22 taxa), Coleoptera (21), and Heteroptera (19) as the most diversified orders, dominated by Chironomidae, Dytiscidae, and Hydrophilidae.

Frequency of occurrence

In Ono Lagoon, very frequent taxa accounted for 11.86% in juvenile and 17.81% in adult *S. molesta*. Frequent taxa ranged from 20.34% to 28.77%, while less frequent taxa, dominant at both stages, represented 64.41% in juveniles and 49.32% in adults. Sporadic taxa showed the lowest occurrence, ranging from 3.39 to 4.11% (Table 3). At Hébé Lagoon, very frequent taxa range from 30.26% (juvenile) to 32.99% (adult). Frequent taxa, the most abundant at both physiological stages, vary from 55.26% (juvenile) to 60.82% (adult). Less frequent taxa exhibit proportions between 13.16% (juvenile) and 6.19% (adult), while sporadic taxa record the lowest percentages, ranging from 1.32% to 0%(Table 3). *Povilla adusta* was among the common taxa at both stages, showing a high occurrence ($F \geq 70\%$).

Diversity indices and density

In Ono lagoon, rarefied richness, Shannon diversity index, and Pielou evenness showed no significant difference between stages (Mann-Whitney test, $p > 0.05$). Aside from evenness, the lowest values of rarefied richness, the Shannon diversity index, and density occur at the juvenile stage, while the highest values are at the adult stage. In Hébé lagoon, only evenness did not differ significantly between stages. In contrast, rarefied richness, the Shannon diversity index, and density are significantly higher at the adult stage (Mann-Whitney test, $p < 0.05$) (Fig. 2).

Table 3
Proportions of very frequent, frequent, low frequent, and sporadic macroinvertebrate taxa collected from *Salvinia molesta* growth stages in Ono and Hébé lagoons.

Lagoons	***Salvinia molesta***	**Very frequent (%)**	**Frequent (%)**	**Low frequent (%)**	**Sporadic (%)**
Ono	SALMOj	11.86	20.34	64.41	3.39
	SALMOa	17.81	28.77	49.32	4.11
Hébé	SALMOj	30.26	55.26	13.16	1.32
	SALMOa	32.99	60.82	6.19	0

Functional Feeding Groups

Figure 3 illustrates the proportions of different trophic groups associated with the physiological stages of *Salvinia molesta* in the two lagoons. Predators clearly dominate, representing 90% (juvenile stage) to 92% (adult stage) in Ono, and about 64% (juvenile and adult stages) in Hébé. Detritivores follow them in both lagoons. In Ono lagoon, phytophages constitute the third dominant group, while in Hébé, this rank is occupied by parasites at 5% (adult stage) and filter feeders at 4% (juvenile stage).

Harmful Taxa

Eleven harmful taxa, including five parasites (*Orobdella* sp., *Erpobdella* sp., *Boreobdella verrucata*, *Theromyzon tessulatum*, and *Haemopis sanguisuga*) and six potential disease vectors (*Aedes* sp., *Culex* sp., *Haematopota* sp., *Diplonychus* sp., *Micronecta* sp., and *Naucoris* sp.), were collected in this study. Hébé lagoon recorded all the harmful taxa except *Micronecta* sp., while Ono lagoon hosted only four of them. Overall, harmful taxa showed higher abundance at the adult than the juvenile stage. Moreover, the number of harmful taxa collected at the adult stage was roughly twice that recorded at the juvenile stage in both hydrosystems (Fig. 4).

Macroinvertebrate communities and environmental factors influence

Redundancy analysis (RDA) conducted on environmental parameters and taxa representing at least 3% of total abundance shows that axes F1 and F2 explain 92.86% of the variance (74.69% and 18.17% respectively), clearly separating samples into two groups. Group I, composed of Hébé lagoon samples, includes thirteen taxa (three Diptera, three Heteroptera, two Pharyngobdelliformes, and one each of

Ephemeroptera, Trichoptera, Coleoptera, Odonata, and Trombidiformes). This group is characterized by pollution-sensitive species (Ephemeroptera, Trichoptera) and is positively correlated with temperature, pH, dissolved oxygen, and conductivity. Group II includes samples from Ono and also contains thirteen taxa. These differ from Hébé samples by higher levels of nitrates, orthophosphates, and transparency. The increase in these parameters seems to favor the abundance of nine Odonata taxa, along with one taxon each of Coleoptera, Diptera, Heteroptera, and Ephemeroptera (Fig. 5).

Discussion

Physico-chemical analysis shows significant differences between the Ono and Hébé lagoons for all parameters except pH. Median temperatures (26.88–30.03°C) reflect warm tropical waters, consistent with Iltis and Lévêque (1982), who noted that water temperatures in Côte d'Ivoire rarely fall below 25°C. The pH showed little variation, remaining slightly acidic (6.1 to 6.5), a typical trend of Ivorian lagoons, influenced by aquatic plant activity that can induce anoxic conditions under the vegetation cover (Eblin et al., 2014). Dissolved oxygen levels were lower in Ono lagoon, which is completely covered by macrophytes. In fact, the accumulation of decaying plants deep within the lagoon increases the amount of biodegradable organic matter and reduces available oxygen (Toft et al., 2003). Water transparency is higher at Ono than at Hébé because dense macrophyte cover enhances water clarity. Conductivity is greater in Hébé than in Ono due to the marine influence associated with the ionic load of air masses from the Atlantic Ocean and the input of mineral salts from the leaching of sandy soils. Regarding nitrate and orthophosphate, the lowest concentrations were recorded in Hébé and the highest in Ono. This peculiarity is linked to the input of continental waters, the drainage of agricultural land, and the resuspension of nutrient salts from sediments (Hammami et al., 2005), worsened by the excessive use of fertilizers in the SCB pineapple plantations.

A total of 144 taxa were identified (77 in Ono and 101 in Hébé), belonging to 49 families, 13 orders, and five classes. Taxonomic richness increased from juvenile to adult stages of *S. molesta*, reflecting the growing structural complexity of the plant, whose developed roots and leaves provide numerous niches for macroinvertebrates. The higher coverage of *S. molesta* in Hébé further supports this pattern, consistent with Mfundisi et al. (2008), who reported that heavily infested habitats host more macroinvertebrates than moderately covered areas. Aquatic insects dominated the assemblages, accounting for 70 out of 77 taxa (Ono) and 86 out of 101 taxa (Hebe). This strong predominance reflects their high diversity in freshwater systems (Tachet et al., 2010). The most represented orders were Coleoptera, Odonata, Heteroptera, and Diptera. In this regard, beetles are highly diverse and exhibit strong ecological adaptability across aquatic habitats (Durand and Lévêque, 1981). Similarly, odonates are predatory insects, well adapted to using macrophytes as substrates and cover for stalking prey (Merritt and Cummins, 1996). In addition, heteropterans and dipterans are also key components of many freshwater systems (Arslan et al., 2010). Notably, in Hébé, several taxa such as Ephemeroptera and Trichoptera were consistently recorded, with an occurrence ranging from 70% to 40%, indicating low water degradation. Diversity indices and density are significantly higher at the adult stage. This stage, free from sampling bias, hosts more taxa and features a well-diversified community, with several taxa being numerically well represented. In both lagoons, evenness exceeds 0.80. These results suggest that macroinvertebrate distribution is relatively balanced between the two physiological stages. Harmful Heteroptera such as *Diplonychus* sp., *Naucoris* sp., and *Micronecta* sp., were found at both stages, with higher frequencies in adults. According to Quentin (2014), these aquatic bugs can carry *Mycobacterium ulcerans* and may transmit Buruli ulcer through their bites. Therefore, the rising abundance of these three Heteroptera species may pose a health risk to lakeside communities, especially fisherfolk and those in frequent contact with the water. Analysis of trophic structure reveals that predators and detritivores are numerically dominant. The high diversity of predators is attributed to the combined effect of abundant prey and the strong diversity of Odonata. As for detritivores, roots and other parts of macrophytes accumulate detritus and a large amount of organic matter, promoting the establishment of detritivorous and collector individuals (Trivinho-Strixino et al., 1997). Redundancy analysis indicates that in Hébé, high temperatures combined with high dissolved oxygen levels favor the abundance of mayflies (*Caenodes* sp.) and caddisflies (*Chimara petri*), both indicators of good water quality. In contrast, within Ono, water transparency, as well as nitrate and orthophosphate concentrations, have a greater influence on the distribution and abundance of taxa.

Conclusion

This study elucidates the influence of *Salvinia molesta* growth stages on the dynamics of macroinvertebrates in lentic ecosystems. Except for pH, which remained acidic in both lagoons, all other physicochemical parameters differed significantly between Hébé and Ono. These environmental disparities, largely driven by local anthropogenic pressures at Ono, also explain the marked differences in macroinvertebrate richness between the two sites. Specifically, taxonomic richness increased from the juvenile to the adult stage of *S. molesta*, rising from 59 to 73 taxa in Ono and from 76 to 97 in Hébé. In addition, rarefied richness, Shannon-Weaver diversity, and density also peaked at the adult stage, reflecting enhanced habitat complexity. Furthermore, while low-frequency taxa dominated Ono, Hébé supported a higher proportion of frequent taxa, indicating a contrast in community composition. The consistent presence of indicator groups (Ephemeroptera and Trichoptera) in Hébé further attests to its better water quality. Conversely, the increased abundance of harmful taxa associated with the adult stage of the water fern may pose health risks to riparian communities. Functionally, predators dominated trophic structures highlighting their regulatory role in macroinvertebrate assemblage dynamics. Finally, macroinvertebrate distribution in Hébé was primarily shaped by conductivity, pH, dissolved oxygen, and temperature, whereas transparency, nitrate, and orthophosphate were the main drivers in Ono.

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Declarations Section

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors

Data availability

Data used in this study are available from the corresponding author upon reasonable request.

Declarations

Acknowledgements

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Funding statement

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Table 2

Table 2 is available in the Supplementary Files section.

Figures

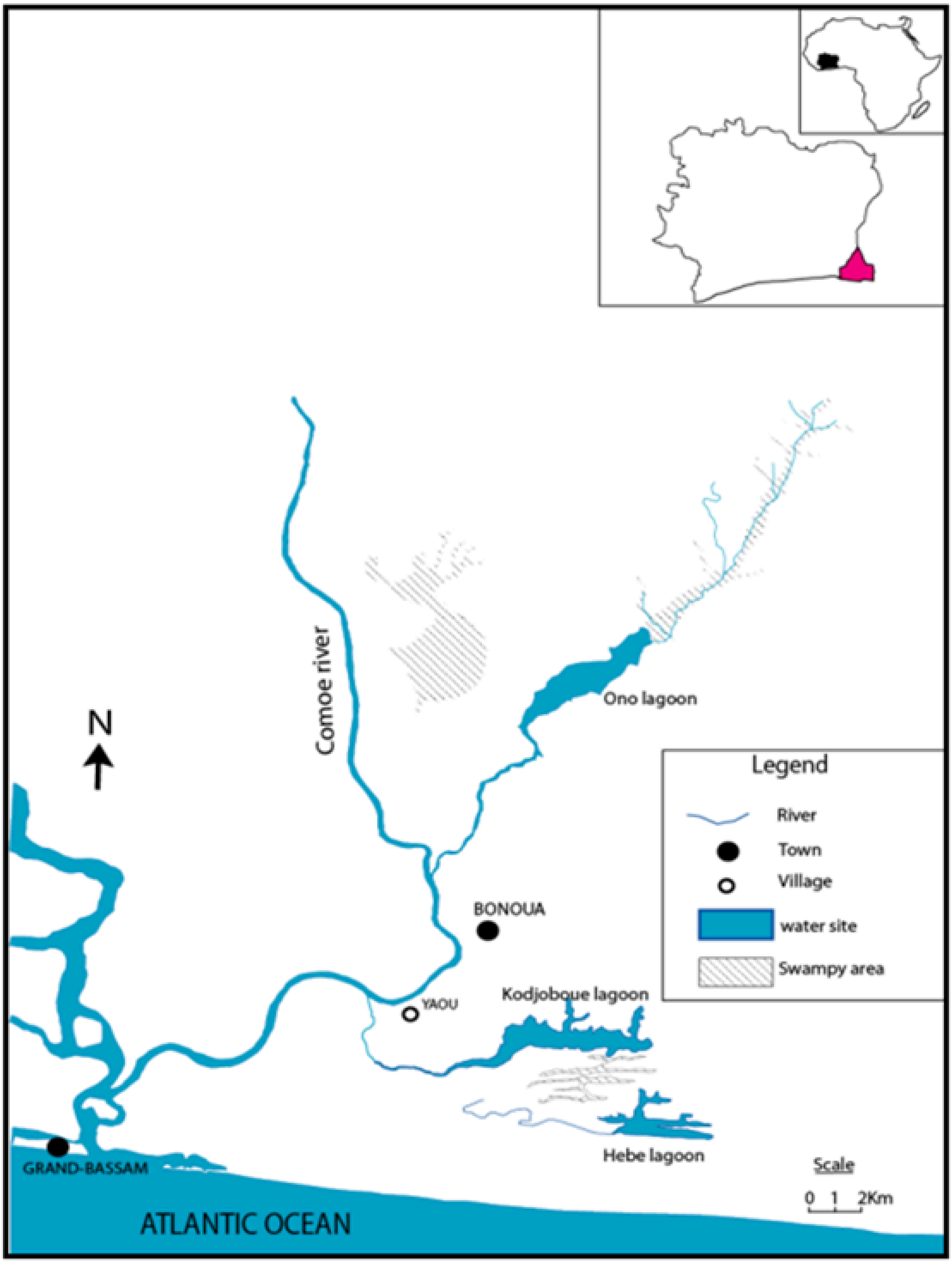

Figure 1

Map of the Sampling Locations

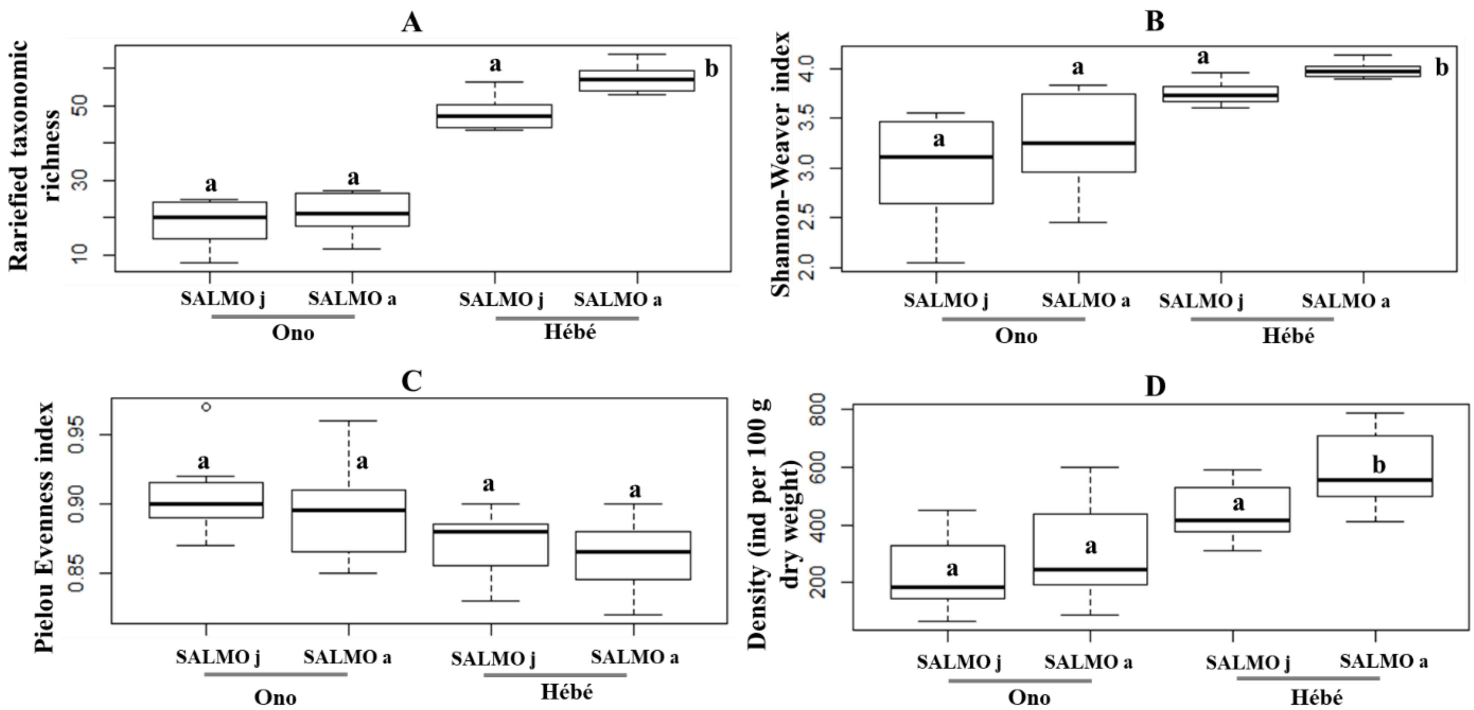

Figure 2

Intra-lagoon variations of Shannon diversity index, Pielou's evenness, and rarefied richness in the Ono and Hébé lagoons. SALMO j = young *Salvinia molesta*; SALMO a = adult *Salvinia molesta*. Median values sharing a common letter (a or b) do not differ significantly (Mann–Whitney test; $p > 0.05$).

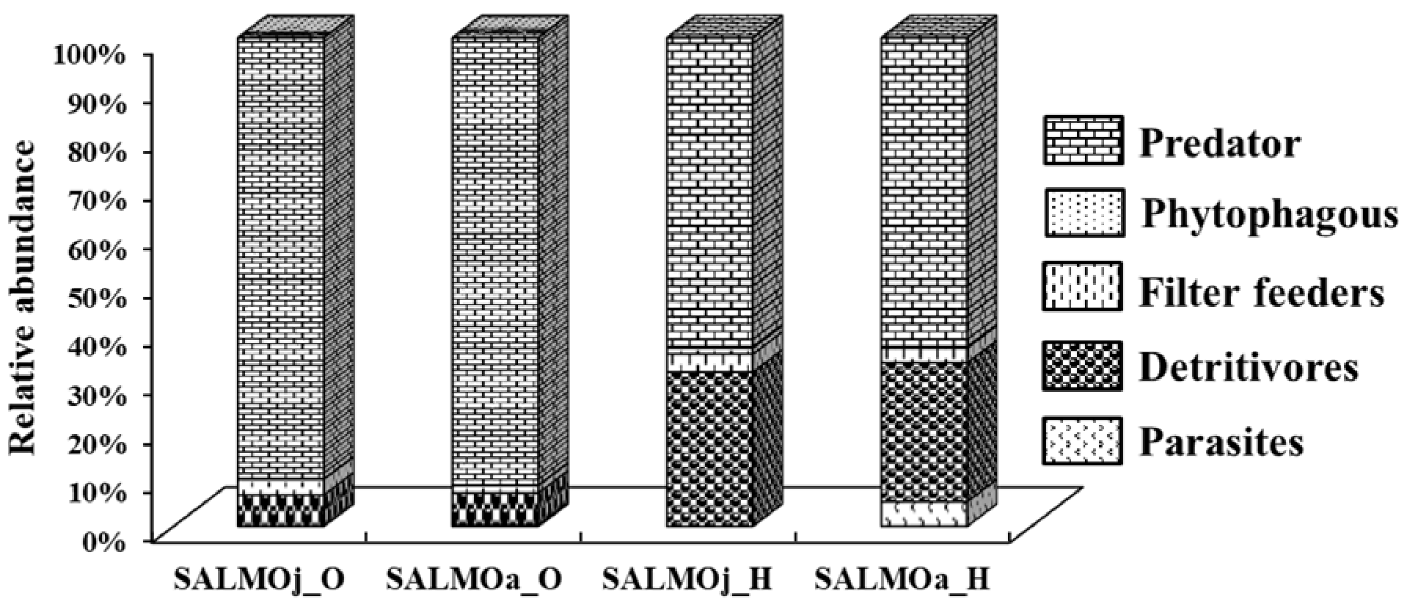

Figure 3

Variations in the trophic structure of macroinvertebrate communities associated with *Salvinia molesta* across growth stages in two lagoons (Ono and Hébé). (SALMO j = young *S. molesta*; SALMO a = adult *S.*

molesta; O = Ono lagoon; H = Hébé lagoon).

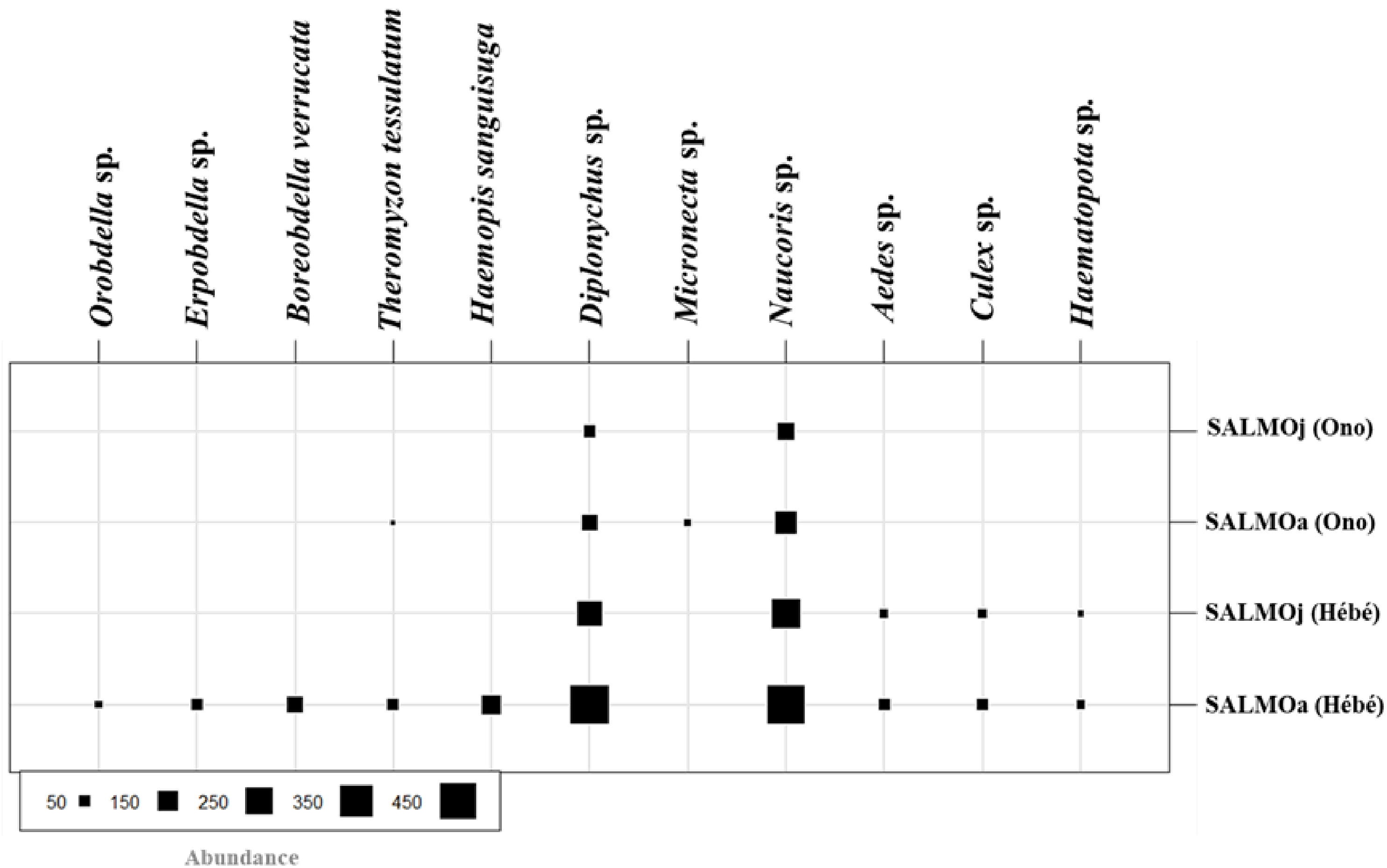

Figure 4

Abundance of harmful taxa collected on *Salvinia molesta* in the two lagoons

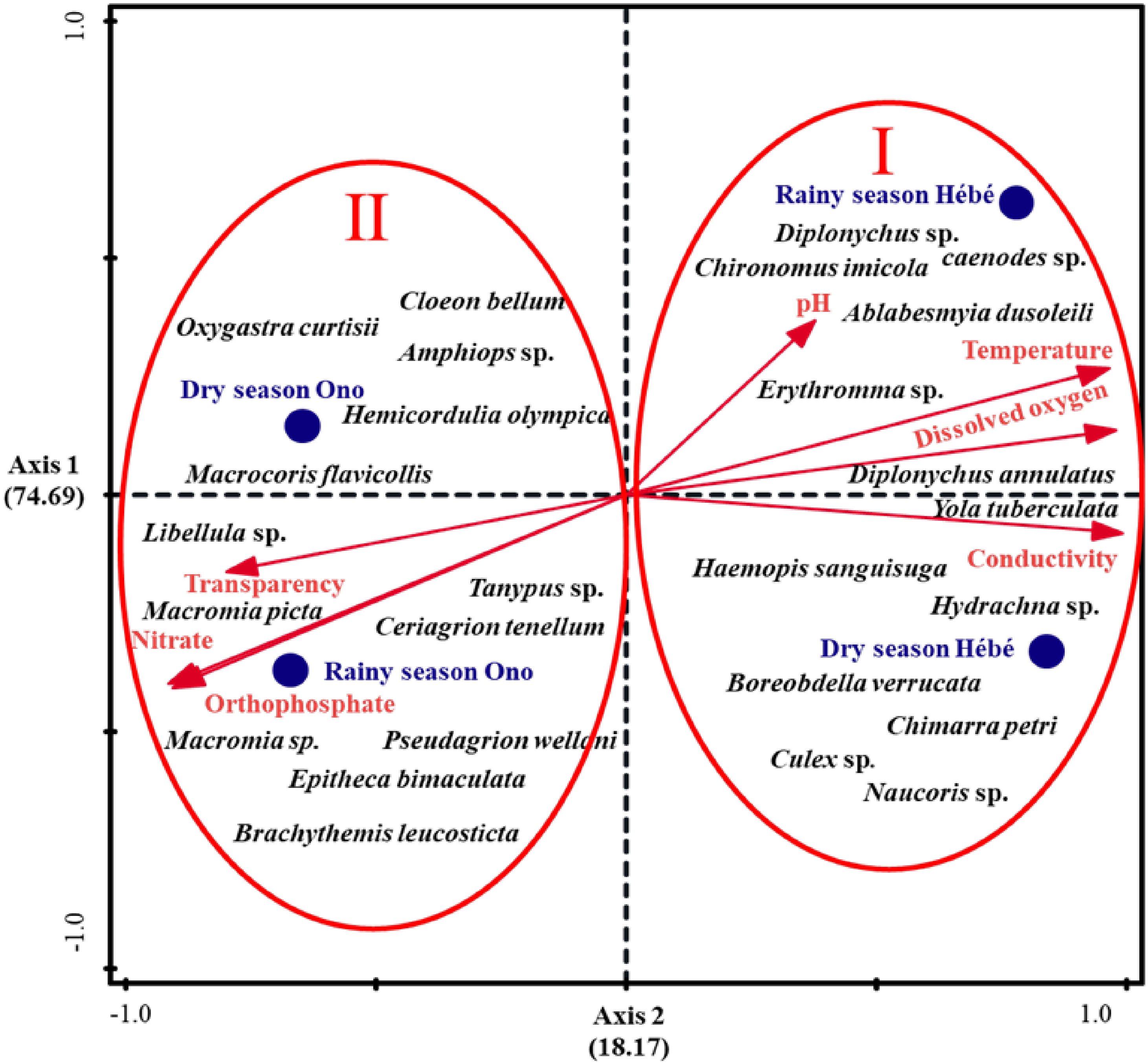

Figure 5

Influence of physicochemical parameters on the abundance of the main aquatic macroinvertebrate taxa collected from the Ono and Hébé lagoons

Supplementary Files

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- Table2.docx