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# Invasion of Water Hyacinth (*Eichhornia crassipes*) Is Associated with Decline in Macrophyte Biodiversity in an Ethiopian Rift-Valley Lake—Abaya

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## Abstract

Macrophytes play critical ecological role in inland water bodies, especially in shallow systems. Water hyacinth (*Eichhornia crassipes*) is an invasive plant species introduced to Ethiopian water bodies around the mid 20th century with recently exacerbated devastating ecological and economic consequences. Here we report the impact of the invasive plant species on macrophyte species assemblage and biodiversity in Lake Abaya, southwestern Ethiopia. We compared four sites in Lake Abaya, two hyacinth infested and two non-infested, each site consisting of 15 plots. Our results showed that water hyacinth affects the macrophyte community composition, abundance and diversity negatively. Even though some macrophyte species from the Poaceae and Cyperaceae families appear to coexist with the alien plant, the invasive species has reduced macrophyte abundance and diversity at the infested sites, and in some cases changed the community to nearly monotypic flora. Our data affirm that water hyacinth has the potential to alter macrophyte composition, abundance and diversity in the wider Ethiopian aquatic ecosystems. A broad & closer, systematic and comprehensive look at the short and long term consequences of its expanding invasion within the framework of specific local environmental, ecological and societal conditions is long-overdue.

## Keywords

Macrophytes, *Eicchornia crassipus*, Composition, Abundance, Wetland

## 1. Introduction

Wetland ecosystems are dynamic in their physical and chemical conditions [1].

Macrophytes, as an integral component of wetlands and shallow lakes, play critical ecological role such as nutrient cycling, and nitrogen removal through denitrification coupled with nitrification. They possess a set of complex adaptations that enable them flourish under a set of dynamic environmental factors: frequent water wave disturbance, siltation and exposure to chemical effluents from terrestrial systems. Competition within the community is also a common feature, especially within plant species having similar ecological strategies, a factor well recognized to affect species distribution in aquatic habitats [2]. Competition among aquatic plant species, however, is much more complex than known for terrestrial plants because aquatic ones can acquire inorganic carbon and nutrients in water [3]. Often, outcompeting species have better morphological and physiological adaptations for nutrient utilization; allelopathic resistance and resistance to anoxic condition than the rest.

Invasion of aquatic habitats by non-native species is a global environmental challenge with serious ecological, social and economic consequences [4]. They do this by altering soil and water chemistry, nutrient cycling, hydrology and disturbance regime of the infested ecosystem. Besides, they affect seedling recruitment blocking seed dispersal through their thick mat growth of stem, root and rhizome [5]. As a result, they often outcompete native plant species and establish a monotypic community.

Water hyacinth (*Eichhornia crassipes*), as an introduced non-native, is a menace to global aquatic environments with serious and devastating consequences. The genus *Eichhornia* has seven species and only one, *i.e. E. crassipes*, seems to hold the exceptional ability to be invasive. This species has the potential to multiply aggressively through clonal means of reproduction, has high growth rate and a highly dispersive floating form [6] [7]. The ecological, social and economic impact of this invasive species is complex and multifaceted: it drastically affects the physical & chemical properties of the water by reducing temperature, pH, biological oxygen demand and nutrient level. High organic load can lead to anoxic conditions that impact not only denizens of the water column, such as fish and zooplankton, but those in the sediment too. Water hyacinth can create unimpenetrable fortress in shallow areas making it difficult to access deeper parts of water bodies for recreation, fishing, transportation etc. The mat can even hamper water flow to hydo-electric dams. In some areas it can provide excessive surface area for intermediate hosts such as snails that transmit waterborne diseases such as schistosomiasis. Its control has been a continuous challenge to ecologists and there seem to be a recent shift in focus from eliminating this invasive plant to making use of its excessive biomass: source of biofuel, carbon for cellulase, electricity, food, antioxidants, medicine, animal feed, fertilizer, and for the manufacture of household articles [8].

Water hyacinth has been reported to invade two major areas of Ethiopia: the Nile basin and the Awash basin extending down to the rift-valley region [9]. Studies on this invasive species in Ethiopia have addressed various aspects such as economic impact, biodiversity loss etc. However there is almost no data on how this aquatic weed is impacting other macrophytes in invaded water bodies. Here we report findings of a comparative study that assessed macrophyte community abundance and biodiversity in one of the most southern Ethiopian lakes, Lake Abaya. We hypothesized that water hyacinth, when present, will outcompete other macrophytes and will overall reduce the biodiversity of macrophyte communities.

# 2. Materials and Methods

## 2.1. Description of Study Area

### 2.1.1. Location of the Study Area

Lake Abaya is one of the two southernmost Rift Valley lakes in Ethiopia. It is the second largest lake in the country next to the non-rift valley—Lake Tana, a lake that has recently been overrun by water hyacinth, similar to Lake Abaya. Abaya is located between 5˚55'9"N to 6˚35'30"N latitude and 37˚36'90"E to 38˚03'45"E longitude (**Figure 1**). The lake, including its islands, has a total area of 1108.9 km$^2$ [10]. It has a maximum length of 79.2 km and with the maximum width of 27.1 km. The mean and the maximum depth are 8.6 m and 24.5 m, respectively [11]. It is located at an average altitude of 1235 meter above sea level [10]. The study was conducted on Lake Abaya, from May to June 2016.

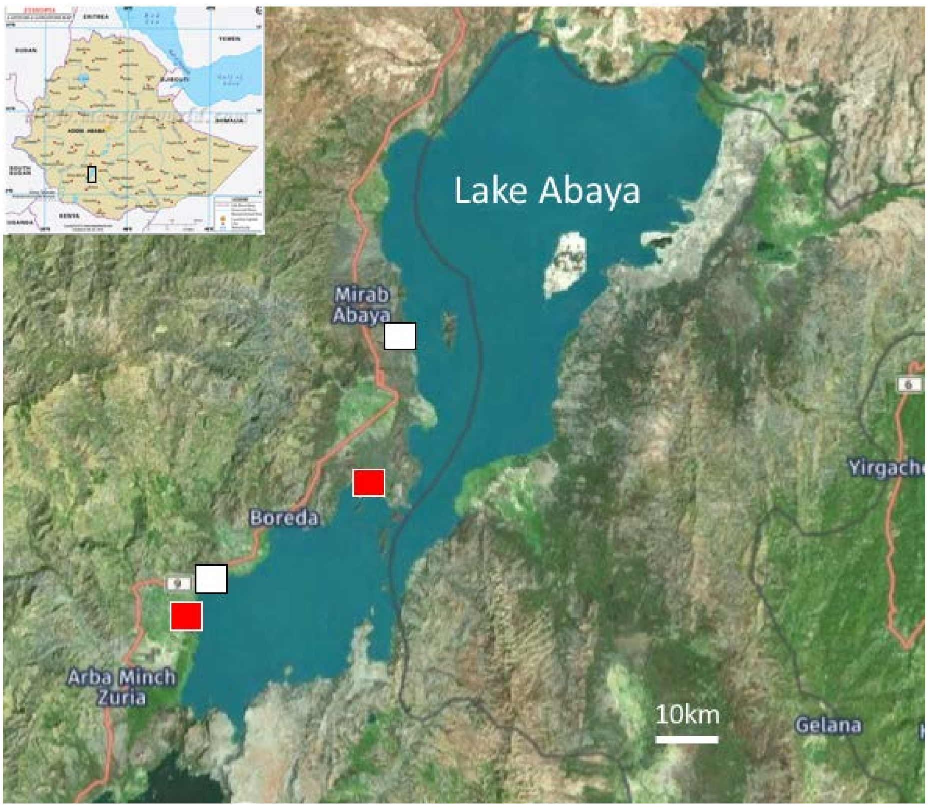


**Figure 1.** Map of study area showing Lake Abaya and sampling sites (red rectangles are sampling sites infested with water hyacinth, white rectangles are non-infested sites; most southern site is numbered 1 in both cases with northern sits as 2). Inset is map of Ethiopia with study area marked in rectangle.

#### 2.1.2. Climate

Based on ten years climate data, (2001-2010), the Lake Abaya basin experiences a bimodal rainfall pattern (**Figure 2**). It has an average annual temperature of 22.9˚C and an average rainfall of 768 mm. The rainy season of the study area ranges from March to November with mean minimum monthly rainfall in January and maximum in May. Hot and dry season is prominent from December to February. The mean minimum daily temperature of the coldest month and the mean maximum temperature of the warmest months are 15.0˚C and 32˚C, respectively.

### 2.2. Data Collection

For macrophyte sampling, a belt transect was laid along the side of the lake (**Figure 1**). Samples were collected early mid of September and early January. Four study sites were selected: two water hyacinth-infested and other two sites free from water hyacinth. A picture of the study sites was taken using cannon 10X pixel camera along the western coast of the lake. In each of the four sites 15 plots were laid, each plot (quadrats) with a size of 0.5 × 0.5 $m^2$ and 25 meter apart from each other [12]. In the field, macrophytes were counted within each plot. A total of 60 quadrats 15 from each site were studied. Collected plant specimens were pressed and tagged and taken to Addis Ababa University National Herbarium for identification using the guide to Flora of Ethiopia and Eritrea.

### 2.3. Data Analyses

Macrophyte species richness, abundance and Simpson's diversity index, and similarity index for plots was calculated using SPSS version and 17 Multiple

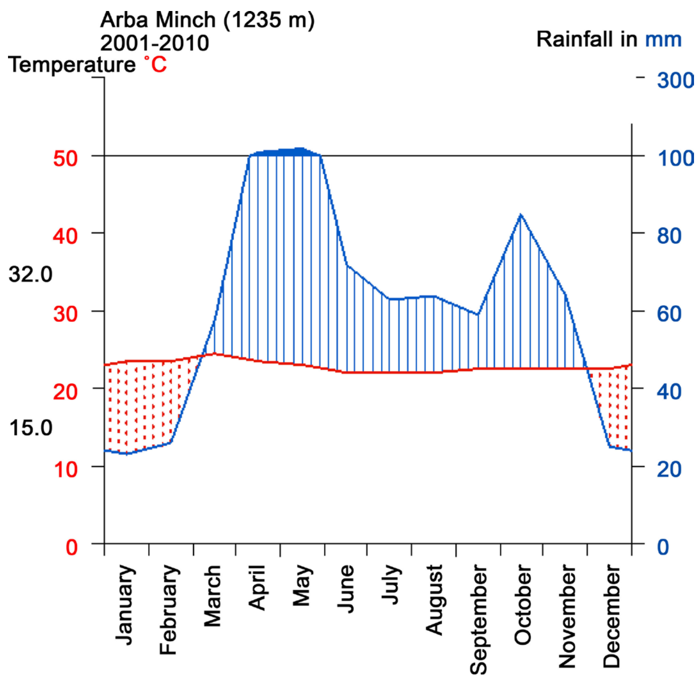


**Figure 2.** Climate diagram of the study area (from 2001-2010).

Correspondence Analyses with two Dimensions was computed. Correlation of degree of the invasive infestation with species abundance of macrophytes was computed Using Microsoft Excel. Ordination by non-parametric multidimensional scaling and clustering of samplings sites based on macrophyte community composition and abundance was done using Primer (version 6) [13]. Macrophyte plant distribution with respect to plant category was analyzed also using orbit lab software.

$$\text{Abundance}(\text{A}) == \frac{\sum \text{individual species}}{\text{Sampled plots}} \tag{1}$$

$$\text{Proportion}(\text{P}) = \frac{\sum \text{individual species}}{\sum \text{all individuals of all species}} \tag{2}$$

$$\text{Relative density}(\text{R}) = \frac{\sum \text{individual species}}{\sum \text{all individuals of all species}} \times 100 \tag{3}$$

$$\text{Dominance} = \frac{\sum \text{plots occupied by a species}}{\sum \text{all plots}(\text{m})} \tag{4}$$

$$\text{Simpson's index}(D) = \frac{\sum n(n-1)}{N(N-1)} \tag{5}$$

$$\text{Evenness} = \frac{D}{S'} \tag{6}$$

$$\text{Richness} = (\text{Dmg}) = \frac{(S-1)}{\text{In}N} \tag{7}$$

where $N$ = total number of organisms; $n$ = number of particular species; $s$ = total number of spp

$$\text{Sorensen index} = \frac{2\text{C}}{\text{A}+\text{B}} \tag{8}$$

where *A*—species number in community '*A*'; *B*—species number in community '*B*'; *C*—common species number in both communities.

## 3. Results and Discussion

We recorded a combined total of 23 macrophyte species belonging to 15 families in all the sites. Out of these, 16 species were observed in the water hyacinth-infested sites whereas 17 were observed in the non-infested sites. Thirteen of the 15 families recorded at Lake Abaya were monospecific, only two families, Cyperaceae and Poaceae, were represented by more than one species. Cyperaceae dominated in terms of diversity with 6 species followed by Poaceae with four species (**Table 1**).

Both the infested sites and non-infested sites had a unique combination of macrophyte communities. Presence of seven macrophyte species, *i.e. Sagittaria latifoli* (Alismaceae), *Cyperus esculentus* (Cyperaceae), *Lemnae equinoctialis* (Lemnaceae), *Pistia stratoides* (Araceae), *Polygonum punctatum* (Polygonaceae), *Potamogeton crispus* (Potamogetonaceae), and *Spharganium americanum* (Sparginaceae), characterized the non-infested sites. These seven species were absent from infested sites.

On the other hand, six other macrophyte species, namely *Bacopa monnieri* (Scrophulariaceae), *Bulbine abyssinica* (Aspodelaceae), *Eichhornia crassipe* (Pontederaceae), *Echinochloa rotundiflora* (Poaceae), *Isoetes* sp. (Isoetaceae), *Leptochloa difusca* (Poaceae) were found only in infested sites. The remaining ten macrophyte species belonging to five families were recorded in both infested and non-infested sites. Of these, with five species in both habitats, the family Cyperaceae seems to flourish under both conditions.

More than half of the macrophyte species at the studied sites in Lake Abaya were emergent, with the remaining 44% comprised of equal proportions of submerged and free floating forms (**Figure 3**). It was interesting to note that seven of the ten species common to both infested and non-infested sites were emergent macrophytes.

## 3.1. Species Richness

Our results showed that species richness in infested sites was 80% - 85% of non-infested sites (**Table 1**). A similar reduction in species richness in plant communities was also reported by [14].

Eleven species were recorded from each of the two infested sites. *E. crassipes* dominated site 1 followed by *Cynodon plectostachyus and Cypress difformis.* Whereas *C. diffusa, B. abyssinica* and *E. rotundiflora* had lower abundance than the three species (**Table 2**). Macrophyte distribution at site 1 was patchy in that though some macrophytes exhibited considerable abundance in some plots, they were rare in most plots. For example, *C. plectostachys* occurred only in 8 plots whereas *E. crassipes* was found in all studied 15 plots of site 1.

*E. crassipes* and *Typha latifolia* dominated the second infested site—site 2, together contributing over 50% of the observed abundance (**Table 2**). The species with the broadest occurrence was *T. latipholia*, with a distribution spanning over nine plots; the remaining nine species had restricted distribution in the studied plots. *Isoetes* sp. is the most abundant species at the site but its distribution within the site was limited confirming the patchy nature of macrophyte distribution in Lake Abaya.

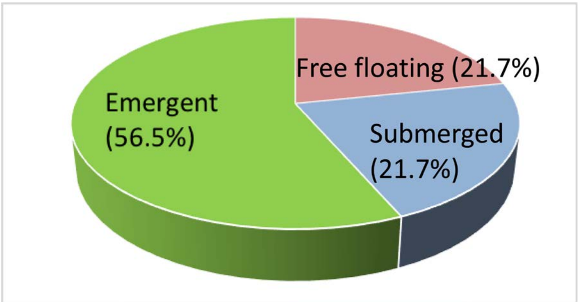


**Figure 3.** Relative abundance of macrophytes with respect to plant category.

**Table 1.** Macrophyte taxa recorded in the four sites of Lake Abaya, Ethiopia. (FF = free floating, Em = emergent, Sm = submerged: + = present, − = absent, Inf = infested site, Noinf = non-infested sites).

| Taxon name | Family | Habit | Category | Infested | Non-infested |
|---|---|---|---|---|---|
| *Bacopa monnieri* | Scrophulariaceae | Herb | Sm | + | − |
| *Bulbine abyssinica* | Aspodelaceae | Shrub | Em | + | − |
| *Commelina diffusa* | Commelinaceae | Herb | Sm | + | + |
| *Costus lucanusianus* | Costaceae | Shrub | Em | + | + |
| *Cynodon dactylon* | Poaceae | Forb | Sm | + | + |
| *Cynodon plectostachyus* | Poaceae | Forb | Sm | + | + |
| *Cyperus difformis* | Cyperaceae | Herb | Em | + | + |
| *Cyperus dives* | Cyperaceae | Herb | Em | + | + |
| *Cyperus esculentus* | Cyperaceae | Herb | Em | − | + |
| *Eichhornia. crassipes* | Pontederaceae | Herb | FF | + | − |
| *Echinochloa rotundiflora* | Poaceae | Forb | Em | + | − |
| *Eleocharis obtuse* | Cyperaceae | Herb | Em | + | + |
| *Isoetes sp.* | Isoetaceae | Herb | FF | + | − |
| *Lemna equinoctialis* | Lemnaceae | Herb | FF | − | + |
| *Leptochloa difusca* | Poaceae | Forb | Sm | + | − |
| *Pistia stratoides* | Araceae | Herb | FF | − | + |
| *Polygonum punctatum* | Polygonaceae | Herb | Em | − | + |
| *Potamogeton crispus* | Potamogetonaceae | Herb | FF | − | + |
| *Rhynchospora corymbosa* | Cyperaceae | Forb | Em | + | + |
| *Sagittaria latifolia* | Alismaceae | Herb | Em | − | + |
| *Schoenoplectus corymbosa* | Cyperaceae | Herb | Em | + | + |
| *Spharganium americanum* | Sparginaceae | Herb | Em | − | + |
| *Typhalatifolia* | Typhaceae | Herb | Em | + | + |

Fourteen macrophyte species were recorded at non-infested site 1 (Table 2). *C. plectostachyus* followed by *C. esculentus,* and *cynodon dactylon* were the most abundant macrophytes at this site. *Polygonum punctatum* and *Lemna equinoctialis* have good number of individuals but were recorded in less than ten plots. *C. lucanusianus, S. americanum* and *S. latifolia* were the least abundant species. Similarly regarding the relative density and dominance, *C. plectostachyus*, *Eleocharis obtusa* and *Isoetes* were at higher rank, respectively, whereas *Rhynchospora corymbosa* and *Sagitaria latifolia* were lower.

Non-infested site 2 had 13 species macrophyte species with *C. plectostachys, S. corymbosa* and *C. difformis* as the most abundant taxa. On the other hand, *R. corymbosa*, *P. punuctatum* and *R. corymbosa* were the three least abundant species at the site (Table 2). Even though *R. corymbosa* and *S. latifolia* seem to have higher abundance value, the relative density and dominance value clearly indicated

**Table 2.** Distribution profile of encountered macrophyte species in the four sites (for formula of parameters refer to "Data Analysis".

| Macrophyte species | Infested Site 1 | | | | | | Infested Site 2 | | | | | | Non-infested Site 1 | | | | | | Non-infested Site 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total № Species | Observed plots | Abundance (A) | Proportion (P) | Relative density (R) | Dominance | Total № Species | Observed plots | Abundance (A) | Proportion (P) | Relative density (R) | Dominance | Total № Species | Observed plots | Abundance (A) | Proportion (P) | Relative density (R) | Dominance | Total № Species | Observed plots | Abundance (A) | Proportion (P) | Relative density (R) | Dominance |
| *Bacopa monnieri* | --- | --- | --- | --- | --- | --- | 10 | 4 | 2.50 | 0.11 | 11.11 | 0.27 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Bulbine abyssinica* | 4 | 2 | 2.00 | 0.02 | 2.27 | 0.13 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Commelina diffusa* | 3 | 2 | 1.50 | 0.02 | 1.70 | 0.13 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 9 | 5 | 1.80 | 0.05 | 4.89 | 0.33 |
| *Costus lucanusianus* | 12 | 3 | 4.00 | 0.07 | 6.82 | 0.20 | --- | --- | --- | --- | --- | --- | 11 | 8 | 1.38 | 0.04 | 4.35 | 0.53 | | | | | | |
| *Cynodon dactylon* | 13 | 7 | 1.86 | 0.07 | 7.39 | 0.47 | 4 | 2 | 2.00 | 0.04 | 4.44 | 0.13 | 14 | 8 | 1.75 | 0.06 | 5.53 | 0.53 | 17 | 6 | 2.83 | 0.09 | 9.24 | 0.40 |
| *Cynodon plectostachyus* | 19 | 8 | 2.38 | 0.11 | 10.80 | 0.53 | 5 | 4 | 1.25 | 0.06 | 5.56 | 0.27 | 65 | 15 | 4.33 | 0.26 | 25.69 | 1.00 | 31 | 7 | 4.43 | 0.17 | 16.85 | 0.47 |
| *Cyperus difformis* | 14 | 7 | 0.52 | 0.08 | 7.95 | 0.47 | 5 | 4 | 1.25 | 0.06 | 5.56 | 0.27 | --- | --- | --- | --- | --- | --- | 25 | 11 | 2.27 | 0.14 | 13.59 | 0.73 |
| *Cyperus dives* | 15 | 7 | 2.14 | 0.09 | 8.52 | 0.47 | | | | | | | --- | --- | --- | --- | --- | --- | 18 | 5 | 3.60 | 0.10 | 9.78 | 0.33 |
| *Cyperus esculentus* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 17 | 6 | 2.83 | 0.07 | 6.72 | 0.40 | --- | --- | --- | --- | --- | --- |
| *Echinochloa rotundiflora* | 5 | 3 | 1.67 | 0.03 | 2.84 | 0.20 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Eichhornia crassipes* | 75 | 15 | 5.00 | 0.43 | 42.61 | 1.00 | 34 | 12 | 2.83 | 0.38 | 37.78 | 0.80 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Eleocharis obtuse* | --- | --- | --- | --- | --- | --- | 3 | 3 | 1.00 | 0.03 | 3.33 | 0.20 | 29 | 11 | 2.64 | 0.11 | 11.46 | 0.73 | 16 | 7 | 2.29 | 0.09 | 8.70 | 0.47 |
| *Isoetes sp.* | --- | --- | --- | --- | --- | --- | 3 | 1 | 3.00 | 0.03 | 3.33 | 0.07 | 21 | 10 | 2.10 | 0.08 | 8.30 | 0.67 | 13 | 7 | 1.86 | 0.07 | 7.07 | 0.47 |
| *Lemna equinoctalis* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 18 | 9 | 2.00 | 0.07 | 7.11 | 0.60 | --- | --- | --- | --- | --- | --- |
| *Leptochloa difusca* | --- | --- | --- | --- | --- | --- | 1 | 1 | 1.00 | 0.01 | 1.11 | 0.07 | | | | | | | --- | --- | --- | --- | --- | --- |
| *Pistia stratoides* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 8 | 5 | 1.60 | 0.03 | 3.16 | 0.33 | 8 | 3 | 2.67 | 0.04 | 4.35 | 0.20 |
| *Polygonum punctatum* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 19 | 8 | 2.38 | 0.08 | 7.51 | 0.53 | 5 | 2 | 2.50 | 0.03 | 2.72 | 0.13 |
| *Potamogeton crispus* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 15 | 8 | 1.88 | 0.06 | 5.93 | 0.53 | | | | | | |
| *Rhynchospora corymbosa* | --- | --- | --- | --- | --- | --- | 2 | 2 | 1.00 | 0.02 | 2.22 | 0.13 | 6 | 3 | 2.00 | 0.02 | 2.37 | 0.20 | 3 | 1 | 3.00 | 0.02 | 1.63 | 0.07 |
| *Sagittaria latifolia* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 2 | 2 | 1.00 | 0.007 | 0.79 | 0.13 | 6 | 2 | 3.00 | 0.03 | 3.26 | 0.13 |
| *Schoenoplectus corymbosus* | 6 | 3 | 2.00 | 0.03 | 3.41 | 0.20 | 5 | 4 | 1.25 | 0.06 | 5.56 | 0.27 | 14 | 7 | 2.00 | 0.06 | 5.53 | 0.47 | 30 | 10 | 3.00 | 0.16 | 16.30 | 0.67 |
| *Spharganium americanum* | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | 14 | 9 | 1.56 | 0.06 | 5.53 | 0.60 | --- | --- | --- | --- | --- | --- |
| *Typha latipholia* | 10 | 6 | 1.67 | 0.06 | 5.68 | 0.40 | 18 | 9 | 2.00 | 0.20 | 20.00 | 0.60 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |

that they a clearly limited distribution at the site.

As it can be seen from the above result, *E. crassipes* was the most dominant macrophyte species in the two infested sites. Infested site-2 seems to be most affected by the invasion of *E. crassipes*, it has the lowest species composition and total number of individuals. Even though the species number is comparable to infested site-1, the total number of individuals is less than observed at infested site-1. The proportion analyses showed that the ratio of water hyacinth over the other macrophytes is 0.43 and 0.38 in infested sites 1 and 2, respectively. This finding also agrees with [15].

In the present study *Pistia stratiodes* was observed only in 5 plots of non-infested sites. Arille [16] discussed the reasons how *E. crassipes* outcompetes other macrophytes like *P. stratiodes* for available nutrients. *Isoetes* is a submerged macrophyte which is affected by the amount of available light. Most likely the thick mat growth of *E. crassipes* in sites-1 and 2 affected the growth of *Isoetes.* This species had higher abundance in non-infested site-1 where there was no shading influence. It is understandable that submerged plants would be more prone to the effect of shading than emergent macrophytes [17]. Our current study confirmed this general notion: the abundance of emergent macrophytes was more than twice that of the submerged ones (**Figure 3**).

At infested site 2, *T. latifolia* had a comparable number of individuals and seems to co-exist with the dominant invasive species (**Figure 4**). Tellez *et al.* [18] indicated that *T. latifolia* is a beneficial plant for the alien species as mechanical supporter during early growth stage. On the other hand, *C. plectostachys* is possibly competing with *E. crassipes* with a clear suppression by the latter when they occur together. For instance, at infested site-1 the number of individual plants of *C. plectostachys* was 19 whereas that of *E. crassipes* was 75 individuals (**Table 2**), but in non-infested site-1 the number of *C. plectostachys* was much higher, *i.e.* 65, in the absence of the invasive species (**Table 2**). However, in infested site-2 the number of *E. crassipes* was reduced by half in the presence of only 5 individuals of *C. plectostachys* (**Table 2**). At the proximate non-infested site-2 *C. plectostachys* seems to recover to 31 individuals in the absence water hyacinth (**Table 2**).

The number of macrophyte species in the community showed significant but negative correlation at (r = 0.904 Pearson correlation) (**Figure 5**). As the number of water hyacinth per plot increases the total number of other macrophyte species in the site decreased. This shows that *E. crassipess* has serious impact on floral diversity. Arille [16] and [18] reported a similar species reduction when invasive species colonize wetlands. Also, Gichugi [17] and Shibu [5] showed, the

**Figure 4.** *Eichornia crassipes* (water hyacinth) infestation in Lake Abaya, Ethiopia.

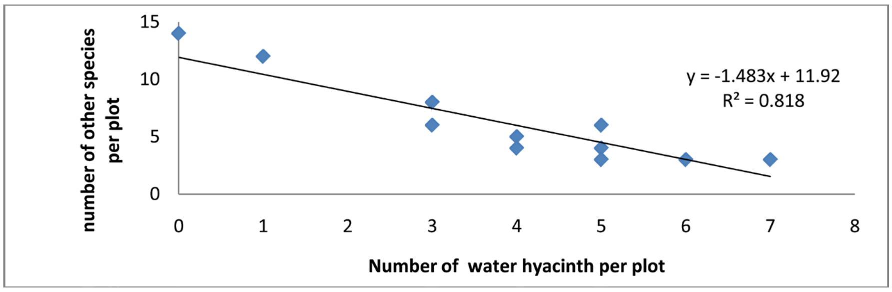


**Figure 5.** Correlation of the number of observed macrophyte species per plot against the density of water hyacinth in Lake Abaya, Ethiopia.

former in Africa lake environment, that the invasion of water hyacinth and other related alien species affect the abundance and diversity of macrophytes resulting in largely monotypic floral community structure.

### 3.2. Community Structure, Similarity & Diversity

Macrophyte communities of the two non-infested sites are more similar with each other than with any of the two infested sites. Furthermore, the level of similarity among non-infested sites was much higher (60%) than macrophyte communities at the two infested sites (45%) (**Table 3**, **Figure 6(a)** & **Figure 6(b)**). Our data also showed that whether a site was infested or non-infested affected macrophyte composition and similarity than physical proximity of sites.

Species diversity at infested sites was lower than diversity at non-infected sites (**Table 4**). Furthermore, evenness of macrophyte communities at infested sites was lower than non-infested sites, indicating the drastic impact of invasive water hyacinth on diversity. However, whether the observed community difference at the two infested sites is related to the length of time since first infestation is currently unknown. A clear understanding of time of infestation and direction of invasion certainly will help us understand better the level of impact and direction of impact progression in the context of local environmental conditions. Macrophyte assemblages are indicated to be impacted by competition [20].

### 3.3. Implications within Local Context

Our data clearly showed that water hyacinth (*E. crassipes*) greatly affects the floristic composition, abundance and diversity of Lake Abaya. Despite the fact that many macrophyte species might have been outcompeted by the invasive species, this study also showed that some macrophyte species, for example, members of the Poaceae and Cyperaceae family, have the ability to co-exist with the alien plant and even possibly control its further spread. This could be due to a number of potential factors such as the specific growth habit of the macrophyte taxa, that may potentially make those tolerant species less prone to the shading effects and other forms of competition of water hyacinth.

We recognize that wetland ecosystems, especially shallow freshwater lakes in the tropics, continue to face sustained human infraction because of their close ties with local economies and the livelihood of communities. Nevertheless, despite

Table 3. Sorensen [19] similarity indexes of macrophyte communities the four study sites (beta diversity) at Lake Abaya, Ethiopia.

| | Infested Site-1 | Infested Site-2 | Non-infested Site-1 | Non-Infested Site-2 |
|---|---|---|---|---|
| Infested Site-1 | 1 | 0.45 | 0.4 | 0.58 |
| Infested Site-2 | | 1 | 0.4 | 0.58 |
| Non-infested Site-1 | | | 1 | 0.66 |
| Non-infested Site-2 | | | | 1 |

Table 4. Macrophyte diversity, evenness and richness in the four study sites at Lake Abaya, Ethiopia.

| Site | H' (Shannon-Weiner Diversity Index) | D (Simpson's index) | Evenness | Richness |
|---|---|---|---|---|
| Infested Site-1 | 1.925 | 0.22 | 0.40 | 1.93 |
| Infested Site-2 | 1.91 | 0.20 | 0.43 | 2.22 |
| Non-infested Site-1 | 2.388 | 0.11 | 0.60 | 2.35 |
| Non-infested Site-2 | 2.29 | 0.11 | 0.67 | 2.13 |

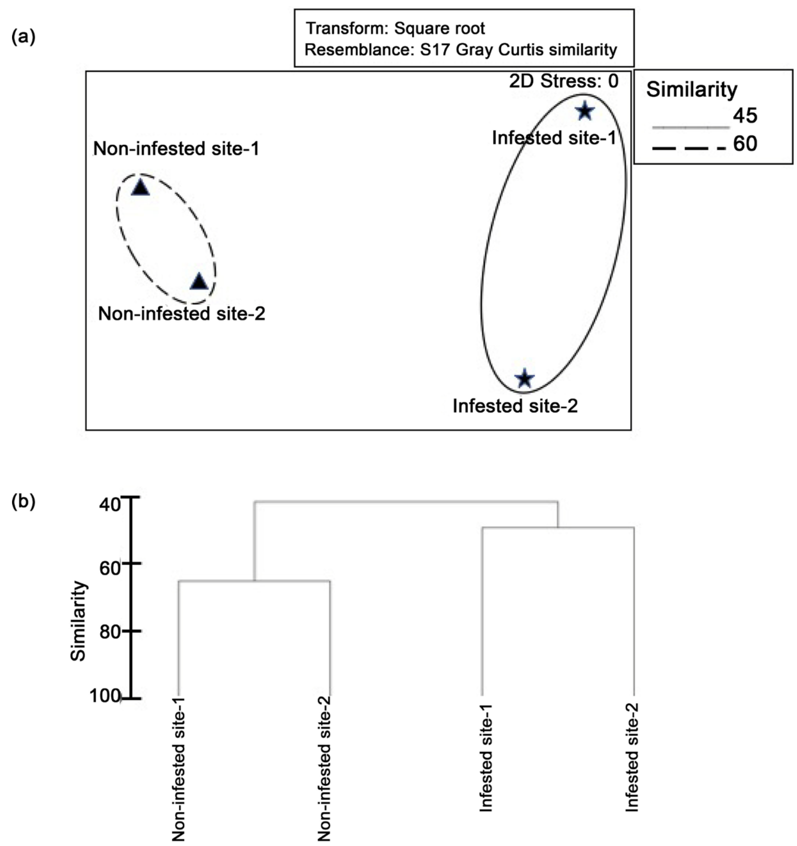


Figure 6. Multivariate analysis of community structure. (a) Non-metric Multidimensional Scaling (MDS) based on Bray-Curtis similarities of macrophyte abundance showing the clear distinction between infested and non-infested sites. Non-infested sites appear to be more similar (60%) that infested sites (45%). (b) Cluster Analysis based on Bray-Curtis similarities using square root transformed data clearly separating macrophyte communities of infested sites from non-infested sites.

their critical economic benefits, freshwater bodies largely remain unexplored in terms of what level of human disturbance tilts their sustainability balance and what level of potential resilience they exhibit towards specific kinds and level of environmental disturbances. Consequently, a comprehensive look at the wider environmental, economic and other impacts of the invasive water hyacinth in Ethiopia is currently not only warranted but overdue.

Water hyacinth has now reached the entire rift valley system and ventured to the largest lake in the country located outside the rift valley—Lake Tana. This has triggered a certain level of local outcry in response to the environmental and economic devastation this invasive species caused in Lake Tana [21]. As a result, researchers are now busy investigating the species where its invasion and impact is deemed critical [22] [21]. These efforts are certainly commendable and encouraging. Studies on this species within the framework of local environmental and social conditions, however, need to go beyond recording status quo of occurrence or impact on fisheries and should be able to develop comprehensive models that predict its temporal invasion expansion patterns within the context of specific water body in question, ecosystem impact and potential disruption.

Invasive macrophytes, apart from their myriad of impacts on non-living anthropocentric values of aquatic habitats, they also impact the living component, *i.e.* microbial, phytoplankton, zooplankton, benthos, macrophytes, fish and other vertebrates, by modifying the physical and chemical environment. Nonetheless, the impact of water hyacinth on ecological communities is known to be non-linear [23]. Availability of specific nutrients, trophic status of water bodies, dominant food web structure, overall community structure and degree of human impact can affect and direct the specific outcome of invasive species such as water hyacinth [24] [25].

Dissecting these and fleshing out the damage by invasive species and their proportional contribution to the overall ecosystem level changes will be key in making an informed decision towards how to address the invasion of water hyacinth in the specific Ethiopian lake ecosystems. For example, aquatic invertebrates generally increase associated with water hyacinth invasion. The refuge effect of submerged macrophytes in lakes on enhancing zooplankton communities and the control of phytoplankton has been demonstrated to be positive [26]. In some cases, invasive, submerged macrophyte species have impacted zoobenthos positively but not the zooplankton [27]. The impact on fish communities, however, is not straightforward and depends largely on original community composition and food web structure. Gerard, and Triest [23] stated "the response of fish communities to water hyacinth is highly dependent on the pre-existing fish community, preferred and available fish habitat, food requirements and availability, physical & chemical conditions and, likely although not proven, water hyacinth density". In addition, "dominant non-native macrophytes may cause significant changes in food web structure of invaded ecosystems" [25]. The impact of an ever-dynamic climate on the macrophyte-phytoplankton productivity balance is also not straight forward and complicates the predictive power of research [28]. All this can be complicated even further by the fact that floating macrophytes in tropical habitats [29] may play key ecological role as a carbon sink—an ecosystem function not in the forefront of concerns in relation to immediate & local human suffering.

Therefore, the need to quantify damage at every level of ecosystem services, impact on human livelihood and disruption of normal human activities cannot be over emphasized. Questions addressing specific environmental conditions in the geographically and limnologically different lakes, Abaya and Tana, for example, would contribute to a better understanding of impact and the development of scalable control measures. Given these generalities, it will be only through critical, systematic, fundamental and comprehensive research that implementable models can be developed that will provide policy makers the needed tools not only to ameliorate the impact on already infested water bodies, but even more to fight the spread of water hyacinth to other uninvaded water bodies through all means including public policy and extensive outreach.

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