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RESEARCH ARTICLE

Socio-ecological complexity in managing long-standing invasive water hyacinth in wetland agriculture and fisheries

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Abstract

1. Managing long-established invasive species in an ecosystem can be complex due to their multifaceted socio-economic roles and use to the stakeholders, an issue requiring more attention.
2. We measured the effects of water hyacinth (*Pontederia crassipes*), one of the world's most notorious invasive aquatic plants, on wetland agriculture, water quality and its use in destructive fish harvesting practices in Bangladesh. Stakeholder knowledge and perceptions regarding water hyacinth were also evaluated.
3. Water hyacinth was recorded in 32% and 36% of surveyed plots in 2021 and 2022, respectively. Using a natural experiment similar to a Before–After–Control–Impact study design, water hyacinth presence was found to negatively impact yields of rice, wheat and jute. Controlling water hyacinth also increased farmers' costs.
4. Water temperature, dissolved oxygen and transparency differed between areas with and without water hyacinth. Deployment of water hyacinth cover patches, constructed by fishermen, to encourage localised aggregation of fish, was associated with higher fish species richness and abundance by 54% and 263%, respectively. Fish caught by subsequent water drawdown were of all sizes and species, including several threatened species, reflecting the non-selective method. It is currently unclear whether this method redistributes fish locally and captures a minor portion of the wetland fish production, but as it becomes more widespread, it poses an increasing threat to fishery sustainability.
5. Local farmers, having limited knowledge about non-native species, regarded water hyacinth as a natural component of the environment due to its presence for over a century in the country. While stakeholders recognised the negative effects of water hyacinth on crops, economically beneficial uses (efficient fish harvesting, as fertilisers and for jute retting) were also recorded.
6. Our findings contribute to increased understanding that invasive species, especially those with long-standing presence in ecosystems, can become deeply embedded in local socio-ecological systems, blurring lines between 'invasive' and

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'naturalised' categories. The dual role of water hyacinth as both an ecological disturbance and a socio-economic resource represents a growing concern in tropical and subtropical regions, where complete eradication is often unfeasible and local communities have developed functional dependencies on the species.

KEYWORDS
biological invasion, destructive fishing, invasive species, non-native species, wetland ecosystem

1 | INTRODUCTION

Wetland ecosystems provide numerous ecosystem services and are important for biodiversity (Costanza et al., 2014; Gardner & Finlayson, 2018) yet are increasingly threatened by anthropogenic activities (Xiong et al., 2023), including the impacts of invasive species (Vantarová et al., 2023). Water hyacinth (*Pontederia crassipes* Mart. [=*Eichhornia crassipes*]) is a floating, perennial aquatic plant, native to the Amazon in tropical South America (Patel, 2012), but which is recognised as one of the 100 world's worst invasive species (IPBES, 2023; Lowe et al., 2000). Due to its fast growth and specific growth form, it can easily block waterways, prevent sunlight penetration, reduce dissolved oxygen, outcompete native aquatic plants and dramatically reduce biodiversity in freshwater ecosystems (Patel, 2012). Water hyacinth has caused concern across many parts of the globe, as it has invaded many ecologically and economically important water bodies in at least 74 countries of Africa, North America, Europe, Asia and Oceania (Abba & Sankarannair, 2024; IPBES, 2023). Water hyacinth may affect fisheries by changing fish community composition through alteration of, or blocking access to, breeding and feeding grounds of fish (Twongo & Howard, 1998; Villamagna & Murphy, 2010) and by reducing fish growth rate (Brown & Maceina, 2002). Moreover, the spread of water hyacinth on seasonally flooded agricultural land can reduce the availability of land for crop cultivation (Damtie et al., 2022) and may further decrease crop production by competing for nutrients (Hossain et al., 2024; Tewabe et al., 2017).

Controlling water hyacinth is economically costly and requires intensive labour, specialised machinery and often frequent treatments (Villamagna & Murphy, 2010; Yismaw et al., 2024). In less developed countries, the control actions often create extra workload and expense for farmers (Damtie et al., 2022). Totally eradicating water hyacinth once it is established is extremely challenging and often fails, primarily due to its prolific reproduction, long-lasting seeds and wide dispersal of propagules by water flow (Albright et al., 2004; Pieterse, 1974; VonBank et al., 2018). Although impacts of water hyacinth on freshwater ecosystems have been quantified (De Groote et al., 2003; Harun et al., 2021; Villamagna & Murphy, 2010), in much of Africa and Asia, their impacts on agriculture remain poorly evaluated (IPBES, 2023).

Bangladesh is a South Asian country where water hyacinth was introduced in the late 19th century from Brazil, as an ornamental flower for water gardens (Pasha, 2012). This species spread through the inland waters across the country, due to its growth form and suitable habitats. Wetlands are major sources of livelihoods, particularly for crop cultivation and seasonal fisheries in southern Asia including Bangladesh (Akter, 2024; Galib et al., 2018; Hossain et al., 2024). Agricultural crops in water hyacinth-infested wetlands may be impacted negatively due to competition for nutrients and space. Nevertheless, there are beneficial uses of water hyacinth. For example, fishers and farmers gather water hyacinth and fix them to bamboo poles and tree branches (locally known as 'katha') to act as fish aggregation devices to create a locally 'improved' habitat for the fishes (i.e. more structure and cover, at which the fishes aggregate; Welcomme, 1979). When seasonal water levels are lowest, the farmers drain out the remaining water from pools using pumps and harvest the fishes exposed. However, this practice may be destructive as it is non-selective and negatively impacts the next year's recruitment of young and brood fishes (Das et al., 2022). Therefore, there might be a trade-off between the negative and positive impacts of water hyacinth, which require full evaluation.

In this study, we evaluated the effects of water hyacinth on agricultural production, fish harvesting efficiency and on water quality in a major wetland of northwest Bangladesh. We also determined knowledge and perception of farmers about water hyacinth. Based on literature and experience, we hypothesised the following: (1) water hyacinth negatively affects crop production and alters water quality parameters; (ii) water hyacinth could be exploited to increase fish harvesting efficiency; and (iii) agricultural farmers have limited knowledge about other potentially beneficial uses (e.g. as fertilisers) of water hyacinth.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted in Gajner Beel, a wetland of approximately 30 km^2 in the northwest district of Pabna, Bangladesh (Table S1). Pabna district is situated between the Lower Ganges and Jamuna (Brahmaputra), two major rivers in South Asia. Gajner Beel is one of the major wetlands in the country for fisheries and agricultural production. The wetland is inundated from the adjacent Jamuna River through sluices for about 4 months (August to November), during

which the water is 2–4 m deep. Thereafter, as the dry-season progresses, the area is drained via sluices to irrigate crops elsewhere (Mazid et al., 2005). For about the last half decade, water hyacinth has become a problem for local farmers due to a dense covering on the water surface during the rainy season, which settles on the agricultural plots when the water is drained. After draining the wetland, a proportion of the water hyacinth remains in the drainage canals where it survives the dry season. Also, some water hyacinth plants may survive in local plots or grow from propagules during the following wet season. The normal farming method in Gajner Beel is to produce agricultural crops twice a year: a wet-season crop (usually May–early September) and a dry-season crop (late November–April). Wet-season crops include rice and jute, whereas rice, wheat, onion and garlic are key dry-season crops. Rice, wheat and jute are traditional crops cultivated for centuries in Bangladesh, whereas onion and garlic have become popular in recent decades. However, onion and garlic require higher production costs, usually by 2–10 times, than the others. For this study, data were collected during both wet and dry cropping seasons in 2021 and 2022.

2.2 | Study approach

2.2.1 | Impacts on crops

We conducted field surveys to determine the impacts of water hyacinth on crop (rice, jute, onion, garlic and wheat) production. Before the surveys, five villages were selected from representative regions of the Gajner Beel, Bogajani (middle), Bamundi (northeast), Paikpara (northwest), Khairan (southwest) and Char Gobindapur (southeast) in order to avoid geographical bias of study plots and the farmers to be interviewed (Table S1).

In 2021, in each village, we conducted a door-to-door survey to identify farmers in the study wetland and a total of 485 people were identified. These farmers were cultivating crops in 2278 agricultural plots (total area: 542.9 ha; mean ± SD: 0.24 ± 0.15 ha; crop-wise data are available in Table S2). We recorded information on their agricultural plots (number and area); status of water hyacinth infestation in plots and its management details (e.g. control measures, associated costs, time required and uses, if any).

We recorded crop types and total production (amount in kg, ready to be sold products) in the study agricultural plots. Between late October and early November, farmers employed control measures for water hyacinth present in their plots. In early December in 2021 and 2022, we surveyed these invaded plots, recorded the types of control measures employed by the farmers, and determined the proportion of the plot area used to pile up water hyacinth, if applicable. After the survey in 2022, all study plots were divided into three types: (i) uninvaded plots (water hyacinth absent in both sampling years; $n = 1455$), (ii) newly invaded plots (water hyacinth absent in 2021 but present in 2022; $n = 88$) and (iii) pre-invaded plots (water hyacinth present in both sampling years; $n = 735$). Three plots were invaded in 2021 but were not invaded in 2022 and therefore excluded from the analysis due to the smaller sample size. Based on 10 randomly selected plots for each category, we determined that fertiliser applications were similar across plot categories for each crop between study years (Table S3).

If daily labourers were employed for controlling water hyacinth, we recorded their number and costs. If this was done by the farmer himself or other members of the family on an unpaid basis, we estimated the equivalent cost by considering the working hours required and standard daily labour costs in the study area.

2.2.2 | Impact on fish harvesting

Many farmers, who own their plots in the deeper parts of the wetland, also harvest fishes from their plots, including 17% of the 266 survey respondents. To determine the effects of water hyacinth on fishes in these areas, we collected fish harvesting data in December of both sampling years from 10 plots where water hyacinth had been used to make shelter-providing fish aggregation devices. We also collected fish data from another 10 plots where no water hyacinth was used. To minimise possible spatial effects, each plot without water hyacinth (hereafter control plots) was chosen as the one closest to a plot with water hyacinth (hereafter treatment plots). The mean distance between treatment and control plots was 42.6 ± 20.7 m. The mean (±SD) sizes of the control and treatment plots were 0.19 ± 0.08 and 0.19 ± 0.07 ha, respectively (paired t-test: $p > 0.05$). In the plots where water hyacinth was used to form fish aggregation devices, water hyacinth usually covered 30%–55% of the water surface. We selected plots with similar coverage (mean ± SD: 41% ± 5%, range: 35%–50%) to minimise the effect of water hyacinth cover proportion on fish aggregation. Catch data were compared between treatment and control groups. Fishes were identified using standard literature (e.g. Rahman, 2005). Nomenclature and classification used in this paper are based on the Fishbase database (Froese & Pauly, 2019). Global and national IUCN redlist conservation status are based on the Global IUCN Redlist (IUCN, 2023) and the Redlist of Fishes of Bangladesh (IUCN_Bangladesh, 2015) databases, respectively.

2.3 | Impact on water quality

Water temperature, water transparency, dissolved oxygen [DO] and pH of the control and treatment plots ($n = 10$ for each) were measured fortnightly, in the first and third week of each month, from August to November in both sampling years. On every sampling day, four measurements of each of the water quality parameters were determined at approximately 20%, 40%, 60% and 80% transverse length locations of every sampling plot between 10.00 and 12.00 h. The mean values were calculated and used in the final analysis. Water temperatures and DO were measured using a digital DO meter (model DO-5510, Lutron electronic); pH and water transparency were measured using a digital Hanna pH meter (model HI 8424) and Secchi disk, respectively.

2.4 | Farmers' perceptions and knowledge on water hyacinth

To determine the knowledge and perceptions of farmers regarding the origin, invasiveness and uses of water hyacinth, we interviewed farmers of newly and pre-invaded plots ($n=266$) in November–December 2022. Before every interview, respondents were informed that the data would be used for research purposes only and their identity would remain anonymous.

2.5 | Data analysis

We used a natural experiment in the wetland, similar to a Before–After–Control–Impact (BACI) approach to determine the impacts of water hyacinth presence on agricultural crop production in two successive years (Galib et al., 2021). The study environment is an open, semi-natural farmed system, affected by natural but variable water hyacinth colonisation. Because of this and the fact that the plots were farmed, it was not possible for us to directly manipulate water hyacinth densities in these plots. We carried out linear mixed-effects modelling (LMM) for each crop in which the time (two levels; 2021 and 2022) and plot groups (three levels; un-, newly and pre-invaded) and their interaction (Time×Group) were considered fixed effects, and repeatedly measured plots with similar cropping and season (for rice only, as this was the main crop) were considered random effects in the LMM models. All the analyses were done using the lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2016) packages in R (R Core Team, 2022). Least square means were also calculated using the emmeans package to estimate the BACI contrast, which is useful in linear contrasts among predictions including interaction contrasts like BA×CI (Searle et al., 1980).

Fish data (control and treatment) were compared using LMM. During analysis, time, groups and their interaction were considered fixed effects, and plot ID and sampling years were considered random effects. Regression was also performed to reveal the relationships between water hyacinth coverage and fish abundance and richness. A Non-metric Multidimensional Scaling (NMDS) (Kruskal & Wish, 1978) ordination plot was generated to visualise the spatial and temporal variation in fish community composition using the 'vegan' package (Oksanen et al., 2018) in R. To examine the dissimilarities among fish communities in habitats with or without water hyacinth, a permutational multivariate analysis of variance (PERMANOVA), using the distance matrix 'Bray', was carried out using the vegan package (Oksanen et al., 2018). Similarity Percentage Analysis (SIMPER), based on the decomposition of the Bray–Curtis dissimilarity index (Clarke, 1993) was used to identify the most responsive taxa to the use of water hyacinth to modify the habitat conditions for fish collection.

For water quality data analysis, LMMs were used, in which 'group' (control and treatment) was considered the fixed factor and sampling months (nested within sampling years) and plot IDs were considered the random factors in the model. Before all analyses, normality of the data was checked and subjected to log transformation to meet the assumptions for the test, if needed (McDonald, 2014).

2.6 | Research ethics

The study was approved by the University of Rajshahi Research Committee for the Faculty of Fisheries (Ref. A/5/52/Fisheries-01/RU) and no permission was required for the fieldwork conducted in this study.

3 | RESULTS

3.1 | Impact on agricultural crops

In 2021, 55% of farmers of 485 interviewed reported water hyacinth in at least one of their agriculture plots and this increased to 67% in 2022. Out of plots surveyed, water hyacinth was recorded in 735 plots (total area: 90 ha; 32% of the total plots) in 2021 and occupied 17% of the total area of the studied plots. In 2022, the number of water hyacinth-invaded plots increased by 12%, from 735 to 823, representing 36% and 21% of the total study plot numbers and areas, respectively (Table S4). Farmers of the plots invaded by water hyacinth either skipped cropping for the season or collected and gathered water hyacinth from the invaded plot by themselves or hired daily labourers, and deposited it in a corner of their plot.

In 2021, farmers did not cultivate any crops in 31 plots in the wet season due to excessive growth of water hyacinth. These represented 4% of the total water hyacinth-invaded plots and <1% of the total area. This number increased to 43 plots (2% of the total plots and <1% of the total area) in 2022 (Table S4). This change was not significant between years (χ^2 test: $p=0.197$).

Significant effects of time (2021 vs. 2022), space (un-, newly and pre-invaded) and their interaction on all crop types occurred, except for interaction effects for garlic and onions (Table 1; Table S5). Crop production between uninvaded and newly invaded sites differed significantly in 2022 but not in 2021. Crop production in pre-invaded plots was significantly lower than other plot types in 2021, which also differed from uninvaded and newly invaded plots in 2022, except for wheat production (Table 1; Figure 1). In 2021, mean rice production was similar between uninvaded ($2711.0\pm168.4\,kg\,ha^{-1}$) and newly invaded plots ($2692.4\pm466.7\,kg\,ha^{-1}$) (LMM: $p>0.05$). In the impacted plots, mean gross crop profit was BDT $92754\pm38{,}350\,ha^{-1}$ (range: BDT 11115–790,400 ha^{-1}) including a mean 15% cost for the water hyacinth management.

3.2 | Impacts on fish harvesting

A total of 46 fish species were recorded from control and treatment plots (Table 2) including seven globally threatened (1 Endangered,

TABLE 1 Before–After (BA) Control–Impact (CI) comparison of different crop production in study wetland plots, Gajner Beel, Bangladesh, in relation to water hyacinth invasion, obtained through linear mixed-effects modelling (LMM).

Crops	Effects	df	*F*	*p*
Rice	Time (BA)	1, 204	14.6	**<0.001**
	Invasion status (CI)	2, 135	55.7	**<0.001**
	Interaction (BA×CI)	2, 204	23.6	**<0.001**
Jute	Time (BA)	1, 609	18.7	**<0.001**
	Invasion status (CI)	2, 609	53.0	**<0.001**
	Interaction (BA×CI)	2, 609	3.4	**0.034**
Onion	Time (BA)	1, 1330	10.7	**0.001**
	Invasion status (CI)	2, 1330	262.9	**<0.001**
	Interaction (BA×CI)	2, 1330	1.6	0.206
Garlic	Time (BA)	1, 40	5.0	**0.030**
	Invasion status (CI)	2, 40	34.3	**<0.001**
	Interaction (BA×CI)	2, 40	2.6	0.089
Wheat	Time (BA)	1, 19	15.2	**<0.001**
	Invasion status (CI)	2, 19	15.1	**<0.001**
	Interaction (BA×CI)	2, 19	7.7	**0.003**

Note: Boldface *p*-values indicate statistically significant differences. Least Square Means values for BACI contrasts are available in Table S5.

3 Vulnerable and 3 Near Threatened) and 15 nationally threatened (1 Critically Endangered, 5 Endangered; 4 Vulnerable and 5 Near Threatened) species (Table 2).

Mean species richness was higher in treatment plots, by 51% in 2021 (38 ± 3.9 species) and 56% in 2022 (39.1 ± 3.5 species), than in control plots (25.1 ± 2.9 species in 2021; 25.1 ± 3.7 species in 2022). Fish abundance was also higher in treatment plots (259,570 ± 78,279 ha^{-1} in 2022; 268,570 ± 79,469 ha^{-1} in 2021) than in control plots (77,252 ± 13,988 ha^{-1} in 2021; 68,327 ± 12,644 ha^{-1} in 2022). Species richness (LMM: $F = 81.9$, $p < 0.001$), abundance ($F = 163.7$, $p < 0.001$; Figure 2) and community composition (PERMANOVA: $df = 1,39$, $F = 71.4$, $p < 0.001$; NMDS, Figure 3) of fishes differed between treatment and control plots. A strong relationship between water hyacinth coverage and fish abundance (polynomial regression: $R^2 = 0.91$, $p < 0.001$) and richness ($R^2 = 0.81$, $p < 0.001$) (Figures S1 and S2) was found. The highest abundance and richness were recorded around 40% water hyacinth coverage, declining on each side of that peak, though extremely high water hyacinth cover was absent (Figures S1 and S2).

Abundance of 45 fish species, out of 47, differed between control and treatment plots (Table S6). Sixteen species contributed more than 70% variation to overall dissimilarity in fish abundance between plot categories (Table S6). Among them, the top three fish species were *Puntius sophore* (11%), *Chanda nama* (9%) and *Parambassis ranga* (7%) (Table S6). Just one species, *Chanda nama*, was more abundant in open water than in habitat dominated by water hyacinth.

3.3 | Impacts on water quality

Water temperature, DO and water transparency differed between control and treatment plots; water temperature was lower (LMM: $F = 549.5$, $p < 0.001$), whereas DO ($F = 171.4$, $p < 0.001$) and water transparency ($F = 234.4$, $p < 0.001$) were higher in the treatment plots with water hyacinth (Figure 4). No difference was recorded for pH (Figure 4).

3.4 | Knowledge and perception of agriculture farmers about water hyacinth

None of the respondents were aware that water hyacinth is a non-native species in Bangladesh. Respondents did not receive any training on water hyacinth management or similar issues. Only 2% of respondents discussed water hyacinth invasion with government officials. All respondents agreed that water hyacinth exerted negative impacts on their crops and increased the production cost. Nearly a quarter (24%) of respondents also found water hyacinth beneficial as it can be used to make fertilisers and fish aggregation devices. A small proportion of respondents were aware that water hyacinth can also be used as cattle feed (4% of respondents), and to aid jute retting, by immersion of jute stems to aid separation of the fibres (4% of respondents). Although 24% of respondents were aware of the possibility of preparing fertilisers using water hyacinth, only 2% of them knew the actual process of making fertilisers from it (Table 3). None of the respondents prepared fertilisers using water hyacinth during the study period. By contrast, 51 % and 17% of respondents used water hyacinth in jute retting, and to make fish aggregation devices, respectively (Table 3). For each household, the mean cost of water hyacinth removal was BDT 20,960 ± 11,671, which was 7% of the total household income (range: 2%–11%).

4 | DISCUSSION

This study provides evidence that water hyacinth can impact crop yield in wet and dry seasons, decreasing farmers' income in a subtropical climate. The impacts reflect characteristics of a typical invasive plant species which can affect the productivity and sustainability of agricultural systems (Vantarová et al., 2023). Our hypotheses were supported. Firstly, multiple agricultural crops in wetland areas are negatively affected by the presence of water hyacinth. Secondly, modification of habitat with water hyacinth increases fish harvesting from deeper areas within the wetland. This invasive aquatic plant can also affect water quality parameters in the wetland. Our third hypothesis, that stakeholders' knowledge about water hyacinth invasiveness and its management is limited, was also supported.

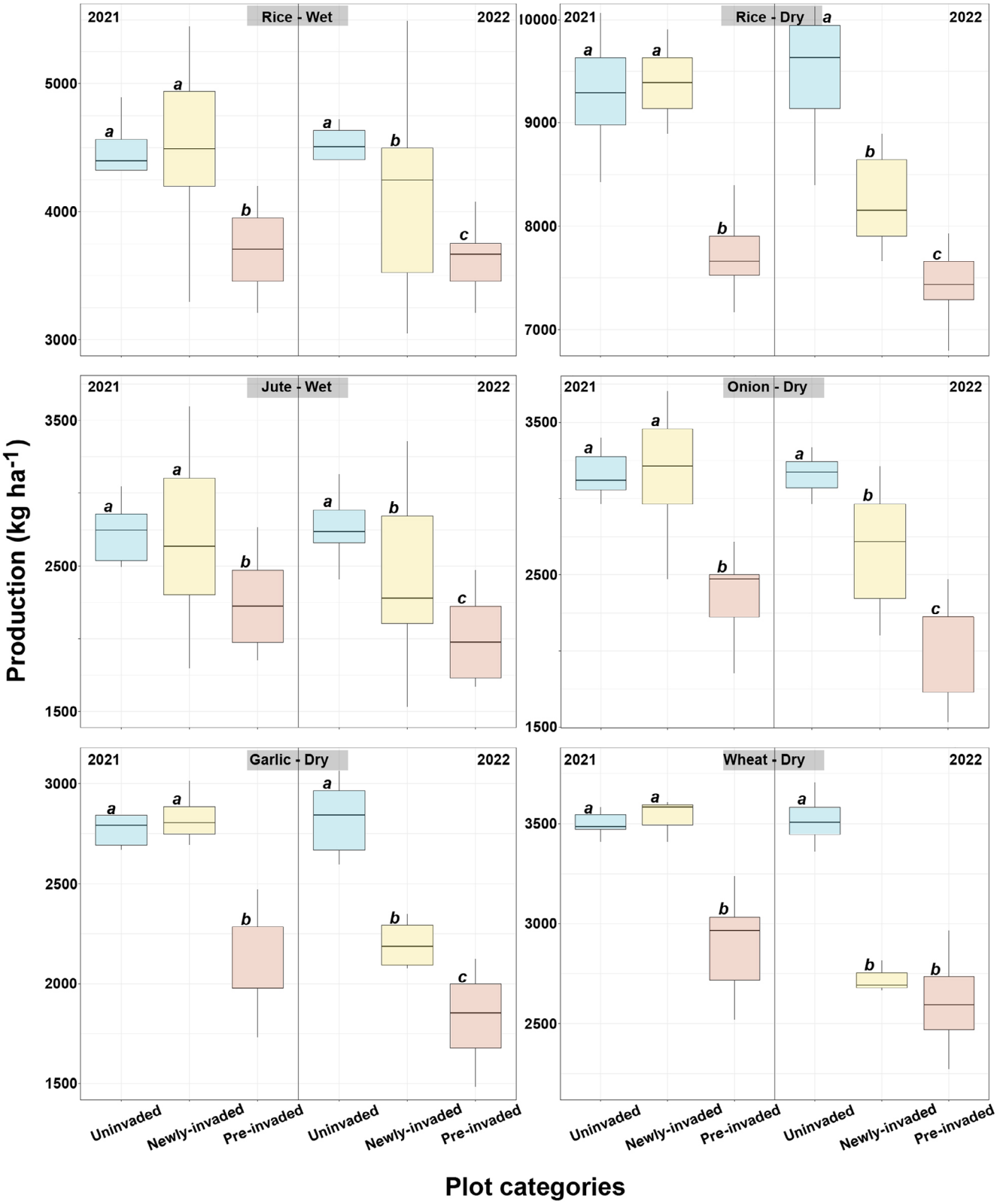


FIGURE 1 Boxplots showing production of various crops in study plot categories (i.e. uninvaded, newly invaded and pre-invaded with water hyacinth) at Gajner Beel, Bangladesh. Categories not sharing the same letter (a–c) differ significantly ($p < 0.05$), determined through one-way analysis of variance (ANOVA) based on two replicates (i.e. sampling years).

4.1 | Water hyacinth invasion and its impacts on crop production

The aggressive growth and competitive nature of water hyacinth has led to its rapid invasion in different parts of the world, posing a threat not only to the health and biodiversity of various environments but also to the livelihoods of people that rely on it (Harun et al., 2021; Villamagna & Murphy, 2010). Water hyacinth in Gajner Beel was more widespread in the wet season, reflecting the favourable environment for proliferation during this time and through its great ability for nutrient extraction from the water (Barua & Kalamdhad, 2016; Damtie et al., 2022; Vantarová et al., 2023). In the dry season, the infestation of water hyacinth was constrained by the lack of sufficient water for growth and dispersal in the wetland. Inland wetlands in Bangladesh, including the study site, are usually drained through canals to facilitate dry-season cropping of rice and other crops, and this can, therefore, limit the spread of water hyacinth within the wetland, but they also act as refuges for its survival during the dry season.

The 4% increase in plots affected by water hyacinth between 2021 and 2022 exemplifies the growth characteristic of successful invasive plants in tropical and subtropical environments (Chong et al., 2021). This aligns with resource competition theory, where light availability is a critical factor determining invasion success (Fine, 2002). In Bangladesh's wetlands, characterised by open habitats with minimal large plants to obstruct sunlight, water hyacinth can grow abundantly and rapidly, leading to high propagule pressure, a factor favourable to invasions globally (Chong et al., 2021). Moreover, according to the biotic resistance hypothesis, higher biodiversity in recipient communities offers more resistance to invading species (Levine & D'Antonio, 1999). Native floating plants in Bangladesh (*Lemna* spp., *Azolla* spp. and *Pistia* spp.) are much smaller than water hyacinth when fully grown, and we did not record any notable abundance of such plants in the study wetland. The dominance of water hyacinth over smaller native species can be speculated and suggests minimal resistance, likely due to its larger size and ability to limit sunlight availability.

We found that all crops were negatively affected by water hyacinth in both wet and dry seasons. Crop growing may be affected negatively in several ways. Firstly, because of skipping cropping in heavily impacted plots, usually in the wet season. Secondly, water hyacinth may restrict farmers from cropping over the entire plot area in both wet and dry seasons. This is because, after removing water hyacinth as a control measure, the majority of farmers tend to gather these plants in a corner of their land, reducing the available land for cultivation and subsequently the crop yield. Thirdly, there may be direct competition for space and nutrients. However, in the dry season, water hyacinth creates dense mats that block irrigation canals and waterways, reducing the amount of water that reaches crops. The need for extra time or additional labour to remove or collect the water hyacinth is another important contributor to the financial loss of the farmers. Farmers often experienced reduced profitability or even net economic loss if water hyacinth growth was too dense. Our results reflect that an invasive aquatic species can exert similar impacts across a range of crops in wetland habitat, as found for some tropical terrestrial invasive plants (e.g. *Parthenium hysterophorus*) (Bajwa et al., 2019).

Our study also reveals that pre-infested plots consistently displayed significantly lower crop production compared to uninvaded and newly invaded plots. This suggests that longer exposure to water hyacinth may have affected the soil productivity to an extent higher than those of newly and uninvaded plots (Unger et al., 2022). This highlights the potential long-term detrimental effects of water hyacinth invasion on agricultural productivity.

The findings of our study align with previous research demonstrating the negative impacts of water hyacinth on wetland economies (Enyew et al., 2020; Honlah et al., 2019; Villamagna & Murphy, 2010). This study moves beyond merely quantifying crop production to emphasise the disruptive nature of water hyacinth. Some farmers were forced to skip entire cropping seasons due to excessive growth of water hyacinth on their plots. This led to lost income and compromised livelihoods for farmers who are dependent on these crops for their food and financial security. These findings have broader implications for tropical regions, highlighting how invasive species such as water hyacinth can threaten agricultural productivity and food security—a pressing concern in many tropical countries (Awumah, 2021; Sileshi et al., 2019). Our study underscores the need for ecosystem-based management that considers ecological dynamics and socio-economic factors to mitigate the impacts of invasive species in tropical wetlands (Al-Mutairi, 2024; Doughan, 2020).

While our results show a 4% increase in water hyacinth affected plots between 2021 and 2022, we recognise that this represents just a snapshot. Longer-term data are needed to confirm whether this increase is part of a sustained pattern of invasion. Additionally, factors such as fertiliser application in adjacent agricultural fields may influence water hyacinth growth, as nutrient availability is crucial for invasive plant success in tropical ecosystems (Chong et al., 2021). Although our study did not examine this aspect, future research could investigate the impact of agricultural practices on the proliferation of water hyacinth. Some potential limitations of our study should also be noted. The density or coverage of water hyacinth in study plots was not controlled and was the result of natural dispersal. Unfortunately, it was not possible to control coverage of water hyacinth in study plots due to a lack of logistical support and the large number of plots. But, we believe that the latter (i.e. large number of plots) has contributed to the reliable findings of this study.

4.2 | Impacts of the use of water hyacinth on fish harvesting and water quality

Invasive aquatic plants including water hyacinth are known for their negative impacts on water quality and aquatic biota (IPBES, 2023; Vantarová et al., 2023; Villamagna & Murphy, 2010). We recorded modifications of water quality although, perhaps unexpectedly, DO

TABLE 2 Fish species recorded in control (habitat without water hyacinth) and treatment (with water hyacinth) plots of the Gajner Beel, Bangladesh ($n = 20$; 10 control and 10 treatment) in 2021 and 2022.

		Mean abundance (ha^{-1})		Conservation status	
Family	Fish species	Control	Treatment	Global[a]	National[b]
Synbranchidae	*Monopterus cuchia* (Hamilton, 1822)	1	124	LC	VU
Mastacembelidae	*Mastacembelus armatus* (Lacepède, 1800)	36	174	LC	EN
	Macrognathus pancalus (Hamilton, 1822)	54	314	LC	LC
	Macrognathus aculeatus (Bloch, 1786)	71	425	LC	NT
Belonidae	*Xenentodon cancila* (Hamilton, 1822)	0	52	LC	LC
Dorosomatidae	*Gudusia chapra* (Hamilton, 1822)	0	193	LC	VU
Botiidae	*Botia dario* (Hamilton, 1822)	67	444	LC	EN
	Botia lohachata (Chaudhuri, 1912)	186	632	LC	EN
Cobitidae	*Lepidocephalichthys guntea* (Hamilton, 1822)	315	2027	LC	LC
	Canthophrys gongota (Hamilton, 1822)	2	92	LC	NT
Cyprinidae	*Pethia phutunio* (Hamilton, 1822)	124	2382	LC	LC
	Pethia ticto (Hamilton, 1822)	389	2678	LC	VU
	Systomus sarana (Hamilton, 1822)	145	966	LC	NT
	Puntius sophore (Hamilton, 1822)	19,045	73,242	LC	LC
	Puntius chola (Hamilton, 1822)	9284	31,118	LC	LC
	Labeo rohita (Hamilton, 1822)	36	241	LC	LC
	Labeo calbasu (Hamilton, 1822)	6	31	LC	LC
	Osteobrama cotio (Hamilton, 1822)	25	159	LC	NT
Danionidae	*Esomus danrica* (Hamilton, 1822)	6166	12,099	LC	LC
	Salmostoma bacaila (Hamilton, 1822)	203	1337	LC	LC
	Amblypharyngodon mola (Hamilton, 1822)	113	431	LC	LC
Nemacheilidae	*Acanthocobitis botia* (Hamilton, 1822)	0	186	LC	LC
Bagridae	*Mystus tengara* (Hamilton, 1822)	100	987	LC	LC
	Mystus cavasius (Hamilton, 1822)	30	325	LC	NT
	Mystus vittatus (Bloch, 1794)	0	65	LC	LC
Clariidae	*Clarias magur* (Hamilton, 1822)	0	88	EN	LC
Heteropneustidae	*Heteropneustes fossilis* (Bloch, 1794)	1002	55,340	LC	LC
Schilbeidae	*Pachypterus atherinoides* (Bloch, 1794)	399	2722	LC	LC
Siluridae	*Wallago attu* (Bloch & Schneider, 1801)	4	61	VU	VU
	Ompok bimaculatus (Bloch, 1794)	0	80	NT	EN
	Ompok pabda (Hamilton, 1822)	3	95	NT	EN
Sisoridae	*Bagarius bagarius* (Hamilton, 1822)	0	47	VU	CR
	Hara hara (Hamilton, 1822)	99	250	LC	LC
Aplocheilidae	*Aplocheilus panchax* (Hamilton, 1822)	146	491	LC	LC
Gobiidae	*Glossogobius giuris* (Hamilton, 1822)	104	573	LC	LC
Ambassidae	*Chanda nama* (Hamilton, 1822)	155,115	49,145	LC	LC
	Parambassis ranga (Hamilton, 1822)	6471	27,767	LC	LC
	Parambassis lala (Hamilton, 1822)	357	1969	NT	LC
Anabantidae	*Anabas testudineus* (Bloch, 1792)	940	5092	LC	LC
Channidae	*Channa punctata* (Bloch, 1793)	2721	11,346	LC	LC
	Channa orientalis (Bloch & Schneider, 1801)	318	1701	VU	LC
	Channa striata (Bloch, 1793)	188	1350	LC	LC
Osphronemidae	*Trichogaster lalius* (Hamilton, 1822)	2219	6215	LC	LC
	Trichogaster chuna (Hamilton, 1822)	0	9	LC	LC
	Trichogaster fasciata (Bloch & Schneider, 1801)	5920	18,864	LC	LC
Tetraodontidae	*Leiodon cutcutia* (Hamilton, 1822)	1	157	LC	LC

Abbreviations: CR, critically endangered; EN, endangered; LC, least concern; NT, near threatened; VU, vulnerable.

[a]IUCN (2023).

[b]IUCN_Bangladesh 2015).

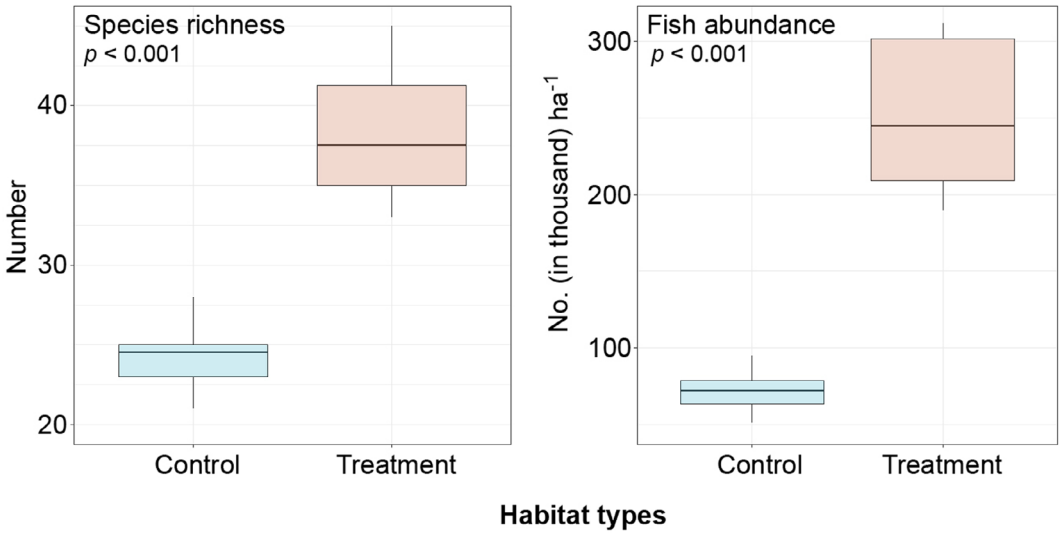
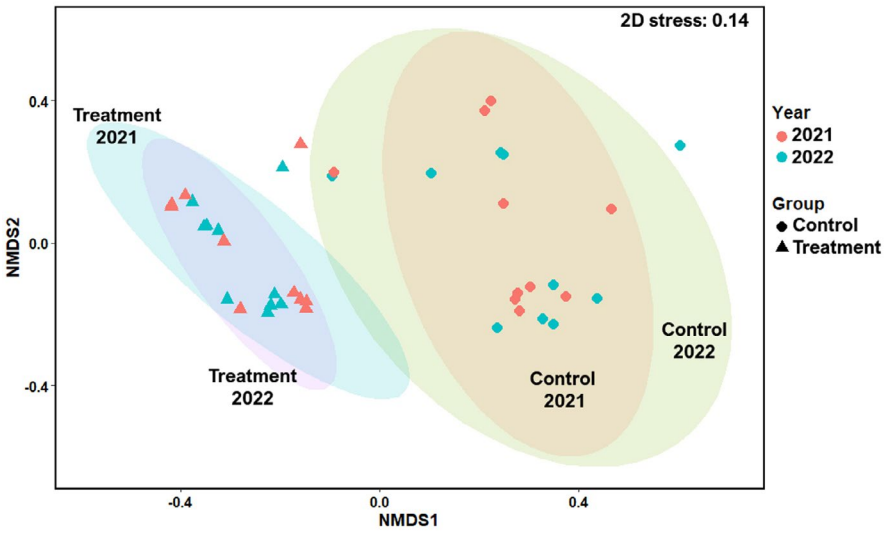


FIGURE 2 Boxplots showing fish species richness and abundance in the control (without use of water hyacinth) and treatment (with water hyacinth) plots in Gajner Beel, Bangladesh.

FIGURE 3 Non-metric multidimensional scaling (NMDS) ordination plot of fish community composition in relation to the use of water hyacinth to modify aquatic habitat for fish harvesting in Gajner Beel, Bangladesh. Ellipses refer to the 95% confidence zones.



was higher in areas with water hyacinth accumulations, though this was likely an effect of reduced water temperature in shaded areas. It should be noted that the DO was measured from the plots where water hyacinth was introduced on purpose as fish aggregation devices and, under these circumstances, water hyacinth did not form a continuous mat over larger areas. Therefore, a plot with 30–50% surface coverage with water hyacinth in an open and comparatively shallow flowing water habitat may have contributed positively to the DO level, through exchange at the air surface and from photosynthesis. In contrast, water hyacinth mats over larger areas could affect the DO negatively through blocking sunlight penetration for photosynthesis-derived oxygen and increased production of organic matter (Oliveira Junior et al., 2021).

Water hyacinth fish aggregation devices were effective in the wetland habitat but made fish vulnerable to efficient but destructive harvesting by dewatering. In wetlands, the water is usually shallow and water temperature starts to increase towards the end of the monsoon. The use of water hyacinth can provide several benefits to the fishes, including refuge provision, especially when water temperature rises due to decreasing water levels, as demonstrated in this study. In addition, aquatic invertebrate diversity and abundance usually increase in the presence of water hyacinth due to increased habitat heterogeneity and structural complexity (Villamagna & Murphy, 2010). Although we did not study the invertebrate community, a similar scenario can be expected in our study wetland. Both shelter and food may have contributed to the high diversity and abundance of fish in wetland areas with water hyacinth (Hossain et al., 2025). Among the commonly found species, several were predominantly predatory in nature (e.g. *Heteropneustes fossilis*, *Anabas testudineus* and *Channa* spp.) and feed on insects, fish and other aquatic animals (Khan et al., 2022; Rahman, 2005)—all of these can be expected in the plots with water hyacinth. In addition, many

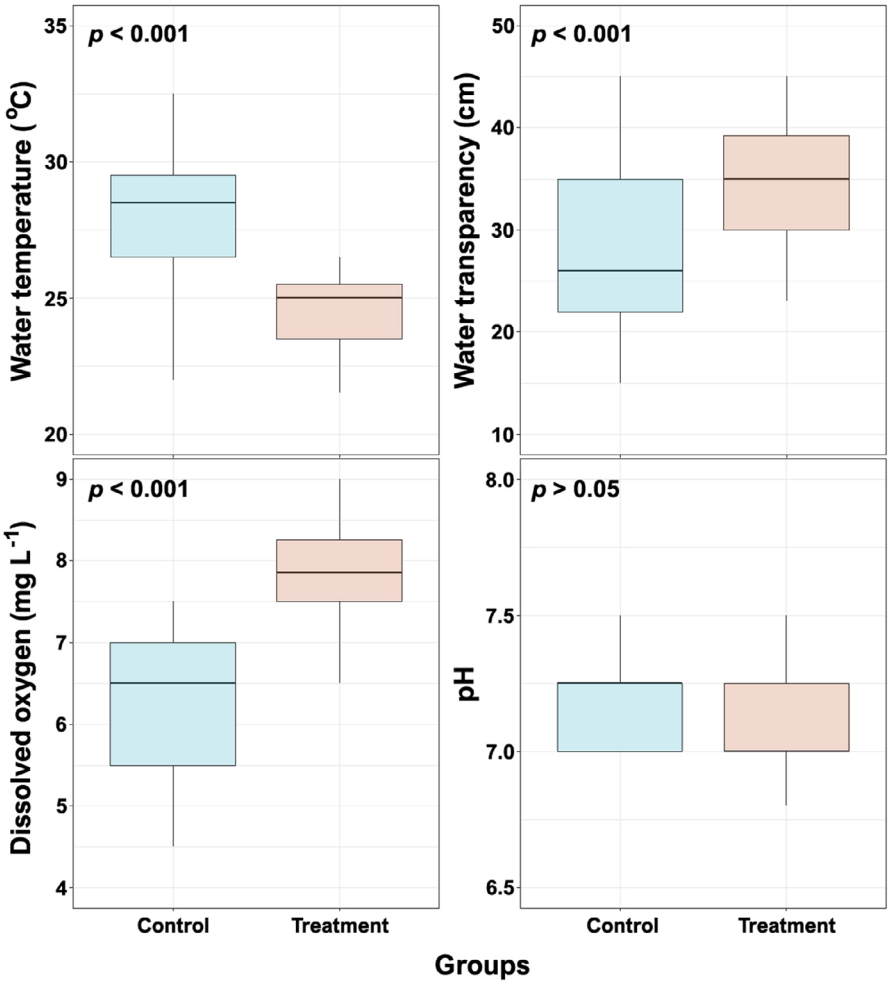


FIGURE 4 Boxplots showing variation in water quality parameters in the control (without use of water hyacinth) and treatment (with water hyacinth) plots in Gajner Beel, Bangladesh.

species (e.g. *Trichogaster* spp. and *Channa* spp.) prefer habitats with aquatic vegetation (Rahman, 2005)—also reflected in our study.

Interviews of the respondents confirmed that use of water hyacinth fish aggregation devices increased the efficiency of harvesting. Several fish species (e.g. *Anabas testudineus* and *Heteropneustes fossilis*) were caught more readily in plots after dewatering as the fishes did not tend to enter into the mud when water hyacinth is present. Several fish species of both global and national conservation status were harvested more in habitats with water hyacinth. These findings confirm that the invasive plant can be used to attract fishes and make them vulnerable to harvesting.

Although an increased fish catch occurred in plots with water hyacinth, potentially benefitting local fishers, this may have detrimental effects on fish populations in the wetland in the near future. The 'katha' fishing practice is destructive in nature (Das et al., 2022), as individuals of all sizes were caught by draining out the water completely, which can negatively affect the sustainability of the fish populations through pre-recruit overfishing (Welcomme, 1979). It is currently unclear whether 'katha' fishing redistributes fishes locally and captures a minor portion of the wetland fish production or whether 'katha' fishing risks overharvesting at the whole wetland scale, especially as the use of this method increases. This needs further research. Also, further studies should be considered to determine the rate of water hyacinth invasion and its impacts on the fish harvest, since there is likely to be a point at which the extent and depth of water hyacinth spread exerts damaging impacts through environmental stress effects such as oxygen depletion (Villamagna & Murphy, 2010).

4.3 | Little awareness and no education programmes

None of the farmers interviewed were aware of the non-native status of water hyacinth; perhaps due to its long historical presence in freshwater habitats in the country (Pasha, 2012). Lack of awareness about non-native and/or invasive plants and their impacts may be common among people (Kumar & Garkoti, 2024). This can pose a hindrance to efforts aimed at promoting effective management strategies and encouraging community participation in control measures of the invasive species (Novoa et al., 2017).

Increasing awareness of people is one of the cost-effective approaches in preventing the spread and introduction of invasive plants (Nguyen et al., 2020). Education programmes and training, both formal and informal, can be very effective in this regard. For example, educational programmes regarding the amount of fertiliser

TABLE 3 Knowledge and perceptions of farmers about water hyacinth at Gajner Beel, Bangladesh.

Knowledge/perception	Answer	Number of respondent (%)
Discussed water hyacinth invasion with govt. officials	Yes	4 (1.5)
	No	262 (98.5)
Impact of water hyacinth	Positive only	0 (0)
	Negative only	203 (76.3)
	Both positive and Negative	63 (23.7)
If positive, what is the reason[a]		
Can be used as cattle feed	10 (3.8)	
Can be used in jute retting	11 (4.2)	
Can be used in modifying fish habitats for increased catch	62 (23.5)	
Can be used as fertiliser	63 (23.9)	
Can be used as barrier to keep the house safe from the flood	2 (0.8)	
If negative, what is the reason		
Responsible for crop production loss and increased cost		266 (100)
Know the procedure to prepare fertiliser from water hyacinth	Yes	5 (1.9)
	No	261 (98.1)
Made fertiliser (e.g. compost) from water hyacinth	Yes	0 (0)
	No	266 (100)
Used as cattle feed	Yes	5 (1.9)
	No	261 (98.1)
Used in jute retting	Yes	135 (50.8)
	No	131 (49.2)
Used as a barrier from flooding	Yes	4 (1.5)
	No	262 (98.5)

[a]Multiple answers were considered.

applied to crop fields may reduce excess leaching (Wang et al., 2021) and therefore could ensure minimum nutrient uptake by invasive plants. In Bangladesh, non-native species are not included in textbooks for primary and secondary school education and therefore awareness through education programmes is scarce. Lack of training of respondents on invasive species makes it more difficult to deal with the biological invasion problem. Unfortunately, this is a common phenomenon in many regions of the world, including South Asian countries (Kumar & Garkoti, 2024). While a small fraction of respondents reported discussing the water hyacinth invasion and potential solutions with government officials, the vast majority had not engaged in such communication. This indicates a potential disconnect between farmers and the relevant authorities regarding the management of invasive species in a locality.

Interestingly, nearly a quarter of the farmers perceived water hyacinth as both beneficial and harmful, citing its possible uses as cattle feed, jute retting, fertiliser and others. However, use of water hyacinth for activities like jute retting and the creation of fish aggregation devices can be harmful to the aquatic habitat and its biota. Jute retting can be responsible for serious degradation in water quality, making the habitat unsuitable for most fishes (Sarker et al., 2022). Nearly a third of farmers were aware of the potential use of water hyacinth as a fertiliser, but less than 2% knew the actual process of making fertilisers. While some of the perceived benefits might be valid, the lack of local knowledge about proper utilisation and potential drawbacks can lead to uninformed practices. Since little or no knowledge of potential uses of water hyacinth was recorded, it is imperative to address this lack of awareness through targeted education to promote its responsible management and discourage potentially harmful practices. While water hyacinth has potential positive uses (e.g. as fertiliser), its negative impacts are of greater concern and, therefore, this invasive plant should not be encouraged in aquatic habitats like wetlands that serve to produce staple crops or fish and provide other important services (e.g. navigation and irrigation).

Our findings contribute to increased understanding that invasive species, especially those with long-standing presence in ecosystems, can become deeply embedded in local socio-ecological systems, blurring lines between 'invasive' and 'naturalised' categories. The dual role of water hyacinth as both an ecological disturbance and a socio-economic resource represents a growing concern in tropical and subtropical regions, where complete eradication is often unfeasible and local communities have developed functional dependencies on the species (Harun et al., 2021). Thus, our study provides a valuable perspective for assessing trade-offs in invasive species management, where ecological damage, cultural familiarity and economic utility intersect (Hanley & Roberts, 2019). Importantly, the approach used could be adapted to evaluate the multifaceted impacts of other entrenched aquatic invasives such as *Salvinia molesta*, *Pistia stratiotes* and *Myriophyllum aquaticum* in floodplain or agricultural systems elsewhere.

5 | CONCLUSIONS

This study demonstrates that the presence of water hyacinth in a South Asian wetland had multiple effects, some negative and others beneficial to local stakeholders. Similarly to most other invasive plants, water hyacinth can increase the production cost and reduce crop yields in subtropical wetlands. However, the use of water hyacinth as a fish aggregation device in traditional fishing methods (i.e. katha) can help to increase the catch efficiency of wild fishes, but its

long-term sustainability should be monitored. Due to the long history of the presence of water hyacinth in Bangladesh, it has lost its 'non-native' status to the farmers who treat it as a nuisance. Given the widespread distribution of this species, limited knowledge of its use, and low income level of the farmers, we should first focus on the potential alternative uses of water hyacinth (e.g. as fertilisers to be used in crop fields and for handicrafts) through training and awareness programmes to offset its negative impacts.

AUTHOR CONTRIBUTIONS

Shams M. Galib designed the study, analysed the data and led the writing of the manuscript. Mobassher Hossain and Nadia S. Kashmi conducted the interviews and collected water quality, fish and crop yield data. Mobassher Hossain, Jingrui Sun and Martyn C. Lucas participated in the writing of the manuscript, data analysis and critically revised the manuscript. All authors gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We declare we have no competing interests.

DATA AVAILABILITY STATEMENT

Data are available from the Zenodo Digital Repository: https://doi.org/10.5281/zenodo.12517497.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Study villages in the Gajner Beel wetland, Pabna district, Bangladesh, their locations and number of farms (=plots) in the respective villages.

Table S2. Crops produced in study plots of Gajner Beel wetland, Bangladesh.

Table S3. Amount of fertiliser (kg) used during production of different crops in Gajner Beel wetland, Bangladesh.

Table S4. Presence of invasive water hyacinth in study agricultural plots ($n = 2278$, 542.9 ha), Gajner Beel wetland, Bangladesh in 2021 and 2022.

Table S5. Least Square Mean values for Before–After–Control–Impact comparisons of agricultural crop production in the Gajner Beel, Bangladesh.

Table S6. Results of the SIMPER (Similarity Percentage) analysis showing response of fish species to habitat with or without water hyacinth in Gajner Beel wetland, Bangladesh and their contribution to the overall variation, based on Bray–Curtis dissimilarity index.

Figure S1. Relationship between water hyacinth cover (%) and fish abundance (number per standard effort) in the study plots, Gajner Beel, Bangladesh, determined through polynomial regression ($R^2 = 0.91$; df = 2.37; $p < 0.001$; $y = 4.85 + 0.035(x) - 0.001(x)^2$).

Figure S2. Relationship between water hyacinth cover and fish richness in the study plots, Gajner Beel, Bangladesh, determined through polynomial regression ($R^2 = 0.81$; df = 2.37; $p < 0.001$; $y = 1.4 + 0.009(x) - 0.0001\ (x)^2$).

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