Environmental Research 243 (2024) 117818

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Engineering aquatic plant community composition on floating treatment wetlands can increase ecosystem multifunctionality

Jonathan Fletcher, Nigel Willby, David Oliver, Richard S. Quilliam *

Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, FK9 4LA, UK

A B S T R A C T

Phytoremediation using floating treatment wetlands (FTWs) is an emerging nature-based solution for freshwater restoration. However, the potential to design these systems by manipulating macrophyte community composition to provide multiple ecosystem services remains unexplored. Using a tank experiment, we simulated aquatic environments impacted by multiple pollutants and employed a comparative ecological approach to design emergent macrophyte communities using the trait of plant stature (plant height) to structure communities. Ecosystem functions were quantified, and a threshold-based method used to compute an ecosystem multifunctionality index that was weighted based on three different management-driven restoration objectives: equal importance, phytoremediation, and regulation and cultural services. Across all restoration scenarios, ecosystem multifunctionality was higher when community types performed more diverse functions. Small emergent plant communities outperformed all other community types due to their increased provision of both regulation and maintenance, cultural, and provisioning services. Conversely, large emergent communities that are more typical candidates for phytoremediation had the highest levels of multifunctionality only when function was lower. Arranging emergent macrophytes in mixed-statured communities led to intermediate or poorer performance both in terms of multifunctionality and specific functions, suggesting that diversity on the plant stature axis leads to negative plant interactions and represents a 'worst of both worlds' combination. Employing comparative ecology to generalise plant selection by stature demonstrates that large emergent macrophytes are more likely to better deliver provision-based services, while small emergent communities can provide additional benefits from cultural and regulatory services. Selecting macrophytes for FTWs employed in freshwater restoration by stature is a simple and widely applicable approach for designing plant communities with predictable outcomes in terms of (multiple) ecosystem service provision and highlights the need for environmental managers to closely align restoration objectives with potential community types.

1. Introduction

Surface waters are vital for supporting people and ecosystems; however, freshwater quantity and quality is under increasing pressure from a growing human population that requires access to safe water (Birk et al., 2020). Freshwaters are negatively impacted by multiple stressors such as diffuse pollution, land-use change and increased storm and drought frequency, which can both impair water quality and reduce ecosystem-service provision (Berger et al., 2017). One strategy to mitigate stressors and restore water bodies in a sustainable way is to use nature-based solutions (NbS; van Rees et al., 2023). Aquatic phytoremediation is an NbS that utilises the capacity of aquatic plants (macrophytes) to uptake, sequester and/or degrade water-borne pollutants (Quilliam et al., 2015; Fletcher et al., 2020; Wang et al., 2002). However, most studies on aquatic phytoremediation focus on selecting macrophytes that optimally target single pollutants (Fletcher et al., 2022); whilst this approach is important it ignores the potential for multiple-pollutant uptake by macrophytes, and the parallel benefits that could be achieved through the additional provision of, for example, biomass production, habitat provision and pollination services.

One key method of deploying macrophytes for freshwater phytoremediation is via floating treatment wetlands (FTWs); these buoyant structures allow emergent macrophytes to grow hydroponically in the water, which facilitates the removal of waterborne pollutants (Chen et al., 2016). FTWs are increasingly used worldwide as a 'best practice' management tool for freshwater restoration in both urban and rural settings spanning a range of temperate and tropical climatic zones (Colares et al., 2020). Despite the increased application of FTWs and a general appreciation of the diverse and important roles played by aquatic vegetation in freshwater systems, there has been little work to determine how FTWs can be designed to support ecosystem functions beyond pollutant removal (Wang et al., 2015).

Ecosystem multifunctionality is the ability of an ecosystem to provide multiple functions and services (Allan et al., 2015). Measures of ecosystem functionality often aim to represent the ability of plant communities to simultaneously provide ecosystem functions into a single metric, whereas plant community phytoremediation has the potential to deliver multiple levels of ecosystem multifunctionality. To

* Corresponding author.
E-mail address: richard.quilliam@stir.ac.uk (R.S. Quilliam).

https://doi.org/10.1016/j.envres.2023.117818
Received 25 July 2023; Received in revised form 25 November 2023; Accepted 27 November 2023
Available online 3 December 2023
0013-9351/

improve ecosystem functioning, and multifunctionality, and increase the ecosystem service provision of phytoremediation, it is important to optimise the composition of the plant community both in terms of its species richness and the functional traits of the component species (Carrillo et al., 2023; Luo et al., 2023). Generally, in terrestrial ecosystems two competing relationships are hypothesised to understand how community composition influences ecosystem function: (1) the mass ratio hypothesis, which proposes that ecosystem functioning is determined by the traits of the most dominant species (species identity) and (2) complementarity effects, which highlight the importance of species and functional diversity leading to reduced competition and increased resource partitioning (Garnier et al., 2016). Relationships between community structure and functioning are not necessarily transferable across different ecosystem types or contexts (Daam et al., 2019) and therefore may not provide the best guide for how to assemble an optimal macrophyte community for freshwater restoration by FTWs (Fletcher et al., 2023).

Previous phytoremediation studies that have attempted to quantify the effects of macrophyte composition on the efficiency of nutrient uptake have shown that species diversity was strongly correlated with removal efficiency of nitrogen (N) based pollutants, whilst specific species were more important for the removal efficiency of phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) (Ge et al., 2015; Geng et al., 2017; Han et al., 2018). Consequently, focusing on the relative importance of species diversity versus species identity can contribute towards a mechanistic understanding of ecosystem functioning in FTWs. However, employing a comparative ecological approach that focuses on a single common plant trait, e.g., plant height, could be used to enhance our understanding of the effects of plant community composition on functioning. Therefore, the aim of this study was to determine how functional plant composition influences the ecosystem service provision of macrophyte communities designed for freshwater restoration. To address this aim and provide a set of principles that can guide community assembly, we focused on the plant stature (i.e. plant height) axis, which is recognized as having a major influence on the associated ecosystem functioning of plant communities (Butterfield and Suding, 2013; Lavorel and Grigulis, 2012). Specifically, our objectives were to (1) identify which types of macrophyte communities are most effective at phytoremediation while concurrently providing a range of ecosystem functions and (2) determine what level of ecosystem multifunctionality each community type can achieve. Anticipated outcomes and priorities differ between environmental managers when restoring freshwaters; and understanding how FTWs can maintain levels of multifunctionality under different restoration objectives is important for making decisions on plant community selection. Therefore, three different restoration objectives were employed in this study in order to crosscut measures of multifunctionality and provide targeted information for environmental managers.

2. Methods

2.1. Plant species and community selection

To determine ecological functionality, six indicators of specific ecosystem functions relevant to phytoremediation were measured (Table 1). Eight macrophyte species (all native to the UK, where they often coexist and are typical components of the vegetation of fertile freshwaters) were selected based on their commonality and differing growth traits. Large-statured emergent monocots (defined as those that typically reach over 150 cm at maturity) *Typha latifolia* (TL), *Glyceria maxima* (GM) and *Phragmites australis* (PA) were selected based on their rapid growth rate, ability to readily take-up nutrients and their widespread use as phytoremediation candidates (Brisson and Chazarenc, 2009; Vymazal, 2007). Smaller flowering emergent herbs including *Myosotis scorpioides* (MS), *Nasturtium officinale* (NO), *Mentha aquatica* (MA), and *Lythrum salicaria* (LS) were selected primarily based on the numerous coloured (blue, white, pink and purple) flowers they produce, which are attractive both to insect pollinators and visually to humans, thus supporting pollination and aesthetic services, while *Eleocharis palustris* (EP), a reported hyperaccumulator of copper (Sakakibara et al., 2011), was selected based on its effective removal efficiency. The eight species were then combined into 11 different community combinations (Table 2) spanning three broad community types: large emergent community (LEC), small emergent community (SEC) and a mixed stature emergent community (MEC) that was a combination of both large and small statured species. The rationale for this was to test if communities differing in diversity of stature (and other interdependent traits) provide enhanced ecosystem multifunctionality. Plant stature (plant height) was used as the key manipulated factor as it correlates with ecosystem functioning and thus enabled a comparison of ecosystem functioning with communities comprised of macrophytes with different plant heights.

Table 1
Ecosystem function, corresponding ecosystem service, and the indicator[a] measured in this study.

Ecosystem function	Ecosystem service type	Ecosystem service	Indicator used
Resource pool utilisation	P, R	Water treatment	Removal efficiency (RE)
Above ground biomass production	P	Forage production	Above ground biomass
Nutrient sequestration	P, R	Nutritional value and nutrient retention	Tissue nutrient concentration
Root biomass production	P, R	Anchorage/below ground structure	Below ground biomass
Dissolved oxygen leakage	R	Provision of (an) aerobic conditions	Dissolved oxygen content
Total visible reproductive organs	C, R	Pollination and aesthetic appeal	Number of flowers per week

Ecosystem Services: Provisioning (P), Regulation & maintenance (R), Cultural (C).
[a] Indicators from (Haines-Young and Potschin, 2018).

2.2. Experimental design

Experiments were carried out in the growing season between July and September 2018 and were housed outside in two open-ended polytunnels (3 m × 2 m x 2 m) (Fig. 1a) with mean air temperature, water

Table 2
Community types and the specific community treatments associated with these groupings.

Community type	Treatment	Plant communities/ treatments	Monoculture/ mixture
Large Emergent community (LEC)	1	*T.lat*	Monoculture
	2	*G.max*	Monoculture
	3	*P.aus*	Monoculture
	4	*T.lat + P.aus*	Bi-culture
	5	*T.lat + G.max*	Bi-culture
	6	*G.max + P.aus*	Bi-culture
	7	*T.lat + P.aus + G.max*	Polyculture
Mixed emergent community (MEC)	*8*	*G.max + E.pal*	Bi-culture
	9	*G.max + N.off + E. pal + L.sal*	Polyculture
Small emergent community (SEC)	*10*	*E.pal*	Monoculture
	11	*M.sco + N.off + M. aqu + L.sal*	Polyculture

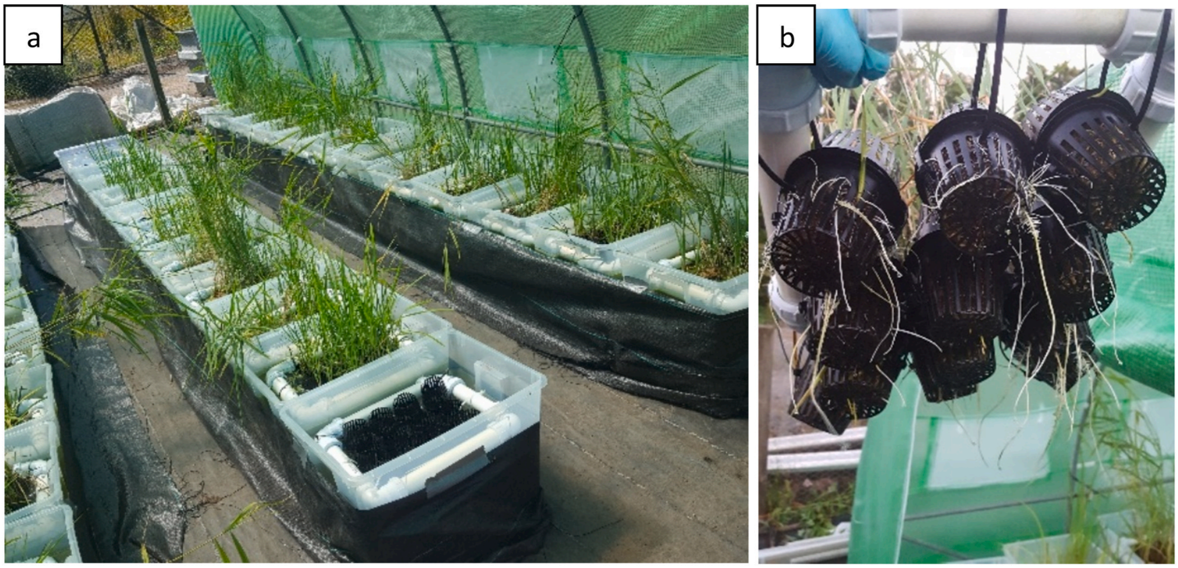

Fig. 1. (a) Experimental FTW mesocosms in open-ended polytunnels; (b) each FTW frame was made up of 12 individual plants.

temperature and light intensity of 14.4 °C, 16.6 °C and 29.5 Klux, respectively.

Macrophytes were planted in experimental FTWs, which were designed to be buoyant and allow hydroponic growth into the growth media. Each FTW was 44 cm × 32 cm and constructed from white 40 mm diameter polyethylene pipe. Twelve modified hydroponic plant pots (12 cm depth and diameter of 7 cm) joined with plastic cable ties were inserted into each FTW frame (Fig. 1b). The 12 planting spaces gave a planting density of 85.2 plants per m^2, which was designed to stimulate natural plant interactions (Pavlineri et al., 2017), and was within the range of previous experimental FTW studies (Jones et al., 2017). Each FTW was placed into a clear polypropylene plastic tank (0.56 × 0.39 × 0.42 m) with a maximum volume of 50 l. There were four replicate mesocosms per treatment, and all replicates were randomly assigned to two adjacent open-ended polytunnels (Fig. 1a).

Mesocosms were designed to simulate a scenario typical of urban and semi-rural environments impacted by multiple pollutants. Each mesocosm contained modified Hoagland's solution (Table S1) (Hoagland and Arnon, 1950), a cocktail of target pollutants (Table 3) and were filled with tap water to 50 l. This volume allowed enough space for root growth and avoided hypoxia. The experiment was designed to simulate a batch-fed wetland with a two-week hydraulic retention time (HRT); therefore, over the ten-week experimental period there were five batches in total. At the start of each batch measurement, all water was removed from each mesocosm, and the container cleaned; a new supply of Hoagland's solution and water was added as described above. To minimise any edge effects, the innermost two mesocosms from each row were re-positioned to the outside end of the row at the beginning of each new batch period; this allowed all mesocosms to occupy a different part of the polytunnel over the course of the experiment.

Table 3
Final concentration of target pollutant in each experimental mesocosm.

Pollutant	Concentration (μg/L)
Ammonia (NH_3)	254
Nitrite (NO_2)	9
Nitrate (NO_3)	2311
Calcium (Ca)	7707
Chromium IV (Cr)	74
Copper (Cu)	34
Iron (Fe)	2289
Potassium (K)	10,619
Magnesium (Mg)	6152
Manganese (Mn)	358
Sodium (Na)	5634
Phosphorus (P)	963
Zinc (Zn)	162

T. latifolia, G. maxima, P. australis, M. aquatica, L. salicaria, and *M. scorpioides* were supplied as pre-grown seedlings (www.salixrw.com), individually propagated in a 110 cm^3 plug. The growth media used for propagation (20 % loam and 80 % peat) was carefully washed from the roots to reduce nutrient input into the mesocosms (Fig. 1). ***N. officinale*** cuttings were collected from an agricultural ditch (56° 12′ 41.4″N 03° 21′ 15.9″W) and *E. palustris* from an urban surface flow wetland (56° 07′ 26.3″N 03° 57′ 17.1″W); both were hydroponically propagated for 10 days in 20 % Hoagland's solution to allow enough root and stem growth to be transplanted.

Individual macrophytes were randomly planted into the experimental FTWs using a random number generator. The base of each plant was wrapped with 2.6–3.4 g of coir fibre to provide support for the stem and protect the roots from direct sunlight. The fresh weight, maximum stem height and number of stems were recorded for each individual plant at the time of planting. All FTWs were then placed in 25 % strength Hoagland's solution for 14 days acclimation prior to the experiment commencing.

2.3. Ecosystem functioning assessment

Water samples were taken from the centre of the mesocosm at a depth of approximately 10 cm. On day 1, four random mesocosms were sampled to obtain a mean of the initial concentrations of pollutants and thereafter every replicate mesocosm was sampled on day 7 and 14 for each batch (each of the five batches lasted 14 days). Within 4 h of collection all samples were vacuum filtered through 1 μm pore-size Whatman glass microfiber filters to remove particulate material. Filtered samples were then preserved for bulk analysis by freezing at −20 °C. Dissolved oxygen was quantified in each mesocosm on day 1, 7 and 14 for each of the five batches using a HACH LDO101 Field Luminescent/Optical sensor (HACH, UK).

A SEAL Analytical AA3 Continuous Segmented Flow Autoanalyzer was used for determination of nitrogen species (NH_3, NO_2, NO_3) using SEAL analytical method No. G-171-96 Revision 8 and No. G-172-96 (Revision 9) (SEAL Analytical). For the analysis of both total phosphate (<1 μm particle size) and metalloid elements, inductively coupled plasma spectrophotometry (ICP-Optical Emission Spectrometer, Thermo

Scientific iCAP 6000 Series ICP; Thermo Scientific, UK) was used. Removal efficiency (RE) was calculated for each batch using Equation (1):

$$\text{Removal efficiency } (\%) = \left(\frac{C_1 - C_2}{C_1} \right) \times 100 \quad [1]$$

where Removal efficiency (%) is the reduction in the concentration of a pollutant C, C_1 being its concentration on day 1 and C_2 its concentration on day 7. Day 7 results were used for this calculation as preliminary trials showed that the greatest concentration of pollutants was removed during this time. The mean removal efficiency from each batch was used to calculate an average for each replicate to assess this continuous function.

At the end of the 10-week experiment, all above-ground and below-ground plant material was harvested separately, and oven dried at 75 °C to achieve a constant dry weight. Representative composite samples of dried above-ground (shoots and leaves) and below-ground (roots and rhizomes) plant parts for each species within each replicate were pulverised using a RETSCH RS200 vibratory disk mill (RETSCH, Germany). The resultant powder was analysed for total C and N using a C:N analyser (FlashSmart NC ORG, ThermoFisher Scientific, UK). Subsamples were also microwave-digested with 70% nitric acid and analysed for P and metalloid element concentration using ICP spectrophotometry. Tissue nutrient concentration was quantified for each species within a community replicate, and a dry biomass-weighted mean per replicate was calculated to generate a representative tissue nutrient concentration. To assess the pollination and potential aesthetic appeal of the plant communities, each week the total number of flower heads in bloom on each individual plant was counted.

2.4. Statistical analyses

All statistical analyses were undertaken using R version 3.5.3 (R Core Team, 2019). Treatment means were calculated for each variable per community type, i.e., for biomass measures a treatment mean of the total standing biomass of each replicate; for tissue nutrient concentration a biomass-weighted mean for each replicate; and for flowers a mean of the total number of flowers per replicate per date. Mean removal efficiency (RE) and dissolved oxygen concentration were determined for each replicate across the experiment duration based on the first seven days of each of the five batches. To compare the RE and concentrations of pollutants in plant tissues between the different plant community types, the data were grouped by either nutrient (P, NH_3, NO_2, NO_3) or major ions (Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Zn), in both cases the total mean was used to compute a global average. The large range of concentrations in above and below-ground tissue meant that each dataset was first normalised by calculating Z-scores for each pollutant before computing the global average. The data from the experiment did not conform to the assumptions required to carry out parametric statistical analysis so non-parametric Kruskal–Wallis tests were used to compare groups and post-hoc Dunn tests employed to identity significant differences with the Bonferroni adjustment used to correct P values (Dinno, 2017).

Multifunctionality was calculated for each plant community type using an established threshold-based approach (Allan et al., 2015). Ecosystem multifunctionality assesses the type of ecological functions that a system delivers in combination with the level at which each function is performed relative to other systems. Functions can be weighted by their importance depending on the management objectives for which the system is designed. This method for assessing multifunctionality assumes that environmental managers can accept a reduced level of ecosystem functioning and that any loss at the level of individual functions, can, dependent on management objectives, be offset by delivery at a lower level across a wider range of functions. Each ecosystem function for every replicate was scored on whether it exceeded a performance threshold of 25 % (low), 50 % (medium) and 75 % (high) of the maximum value across all the replicate mesocosms. To avoid the influence of outlier values, the maximum value was based on the mean of the highest five results. These three thresholds were chosen to cover a range of performance levels across the dataset. Multifunctionality was calculated using the function 'multidiv', available from git-hub. com/eric-allan/multidiversity. In the assessment of multifunctionality, all data input was mean-centred and Z-scored. To quantify multifunctionality according to different freshwater restoration objectives the ecosystem functions were weighted differently (Table 4). The equal importance objective was based on there being no preference for any service, with the phytoremediation objective prioritising removal efficiency of both the nutrient and major ions-type of pollutants and above-ground harvestable plant parts (biomass and above-ground tissue concentration). In comparison, the regulating and cultural services objective applied greater weighting to flower production (as an indicator of pollination and aesthetics services), dissolved oxygen and below ground biomass.

3. Results

3.1. Ecosystem functioning

The composition of macrophyte communities (based on stature) intended for phytoremediation had an impact on ecosystem service provision. Large emergent plant communities (LECs) removed more nutrients from the water column with an average removal efficiency (RE) of 76 % compared to 45 % in small emergent communities (SECs). Mixed stature emergent communities (MECs) were intermediate, with an average RE of 60 %, but were not significantly different from their large or small statured counterparts (Fig. 2). In contrast, there was limited difference in the capacity of the three different community types to remove major ions from the water column (Fig. 2). MECs removed 45 % of major ions while LECs and SECs only removed a further 2–3 % more, and only LECs showed a significantly higher RE (Fig. 2) ($P < 0.05$). However, there was a degree of specificity in the removal of nutrients and major ions for each plant community type: LECs were more efficient at removing nutrients (P and N species) and in general more inorganic elements, including both micro and macronutrients (data not shown). The unplanted control mesocosms had the highest levels of dissolved oxygen; whilst of the planted treatments, mesocosms with MECs had the highest DO concentration, which was significantly higher ($P < 0.05$) than the mesocosms with LECs (data not shown).

There was no significant difference between LECs and SECs in above-ground mean normalised nutrient and major ion tissue concentrations (Fig. 3), despite LECs having numerically higher mean values. This implies that these two community types have a similar capacity to sequester and translocate pollutants to above-ground tissue. Conversely, both SECs and LECs had significantly higher above-ground mean normalised nutrient and major ion tissue concentrations compared to MECs ($P < 0.05$). Mirroring these collective results there were no significant

Table 4
Ecosystem functions used in the calculation of ecosystem multifunctionality with the weighted proportion of each for the restoration objective.

Ecosystem function	Equal importance	Phytoremediation	Regulation and cultural
RE nutrients	0.125	0.3	0.05
RE major ions	0.125	0.3	0.05
AG tissue	0.125	0.15	0.025
BG tissue	0.125	0.01	0.025
Dissolved oxygen	0.125	0.05	0.1
AG biomass	0.125	0.15	0.05
BG biomass	0.125	0.03	0.1
Flowers	0.125	0.01	0.6

RE: removal efficiency; AG: above ground; BG: below ground.

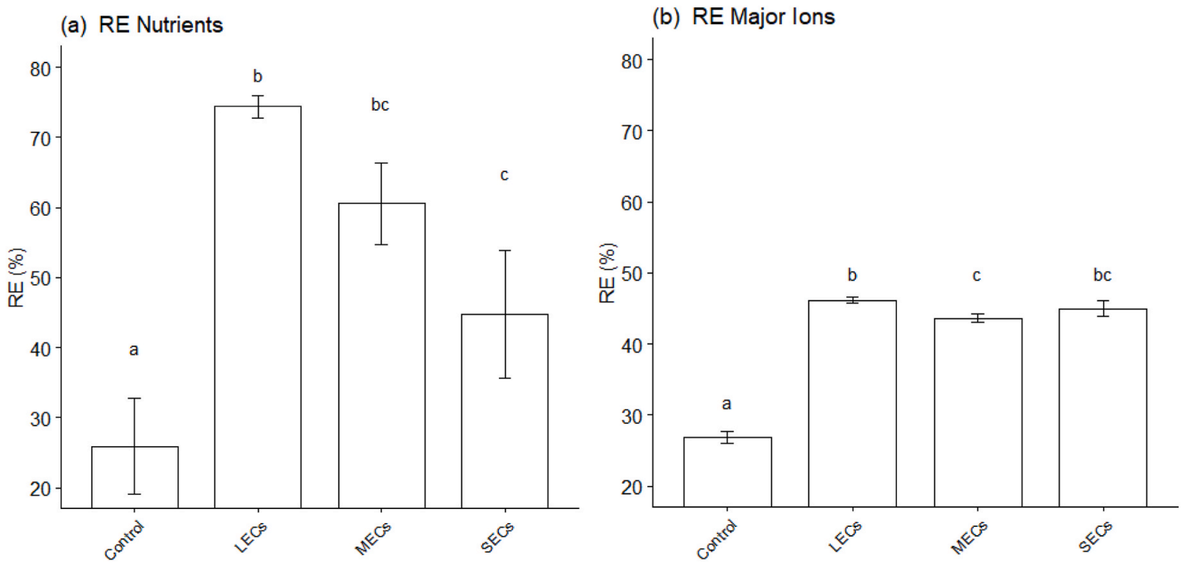

Fig. 2. Overall mean removal efficiency (RE) for large statured emergent communities (LECs) ($n = 80$), mixed statured communities (MECs) ($n = 40$), small statured communities (SECs) ($n = 40$) and unplanted controls ($n = 40$) by (a) Nutrients and (b) RE Major Ions after seven days (50 % of HRT). Error bars show the standard error of the mean, and bars with different letters are significantly different from each other ($P < 0.05$).

differences between LECs and SECs for specific pollutants. Below-ground mean normalised tissue concentrations of both nutrients and major ions were significantly higher by two orders of magnitude in LECs compared to MECs and SECs ($P < 0.05$) (Fig. 3). However, there was no significant difference between MECs and SECs in below-ground mean normalised tissue concentrations suggesting that uptake capacity and below-ground storage were similar (Fig. 3).

In terms of plant allometry and associated element storage, SECs and MECs had a significantly higher shoot to root tissue ratio for most elements including Ca, Cr, Cu, Fe, P, Na and Zn ($P < 0.05$) compared to LECs (data not shown). However, above-ground biomass was not significantly different between the three community types (Fig. 4) despite LECs having a significantly higher below-ground biomass than SECs ($P < 0.05$). MECs were intermediate and not significantly different from either LECs or SECs. Finally, SECs and MECs produced significantly higher ($P < 0.05$) numbers of flowers than LECs (data not shown).

3.2. *Ecosystem multifunctionality*

Structuring plant communities in FTWs by stature led to differences in ecosystem multifunctionality (EM) at varying performance thresholds. At the high-performance threshold (75 %) the EM values for SECs were significantly higher than all other plant community types regardless of objective ($P < 0.05$) (Fig. 5). SECs also showed significantly higher levels of EM in the medium performance threshold in the cultural and regulation objectives ($P < 0.05$). Conversely, multiple ecosystem services of LECs were most optimal at lower performance thresholds, with significantly higher levels of EM compared to SECs and MECs in the 25 % (low) and 50 % (medium) thresholds in the equal importance objective ($P < 0.05$) (Fig. 5). Similarly, under the 25 % (low) threshold of the phytoremediation objective the EM value for LECs was significantly higher than other community types ($P < 0.05$). Across all objectives and performance thresholds the EM values for MECs were significantly lower than other community types ($P < 0.05$), or not significantly different from the LECs (Fig. 5).

In general, EM values decreased with increasing performance thresholds indicating a reduction in the total amount of functions delivered at higher levels (Fig. 5) ($P < 0.05$, for all pairwise comparisons). Within plant community types there was variation in the EM values due to the influence of specific species combinations. Under the equal importance and phytoremediation objectives, TL + PA, TL, GM + PA, TL + PA + GM from the LEC had the highest EM values among all plant combinations for low to medium performance thresholds (data not shown). In the high-performance threshold under these objectives, the TL community remained the highest of the LECs and comparable to the polyculture SEC. The polyculture community MS + NO + MA + LS consistently demonstrated higher levels of EM compared to its monospecific small emergent counterpart community EP and exceeded all communities at all performance thresholds in the culturing and supporting objective.

4. Discussion

We hypothesised that structuring plant communities by stature would result in differences in ecosystem functions and capacity for multifunctionality. Arranging macrophyte communities for phytoremediation this way has a clear impact on the outcomes of freshwater restoration and on the (multiple) ecosystem service provision potential of these FTW systems. Our results suggest that SECs deliver the best ecosystem multifunctionality (EM) at higher performance levels compared to both LECs and MECs. SECs are characteristically different from LECs in their ability to produce numerous flowers, and this function consistently results in an overall higher EM value. LECs were unable to achieve the same high-performance thresholds in key ecosystem functions, including, surprisingly, nutrient and major ion removal efficiency (RE), likely leading to the lower EM. While there were clearly some individual plant communities that have a high level of multifunctionality within the LEC community type (often involving *Typha latifolia*), generally this grouping produced higher EM only at the low to medium performance levels. Although the SECs performed better *per se*, the overall trend of decreasing ecosystem multifunctionality with increased threshold level, suggests that fewer functions can be performed at a high level for all community types. Therefore, a trade-off between an overall high multifunctionality and optimum performance of some individual functions, such as pollutant removal, should be anticipated. This is consistent with terrestrial-based studies that show that some ecosystem functions can be negatively impacted by increases in performance thresholds (Allan et al., 2015).

The higher EM values for LECs at lower performance thresholds suggest that more functions are performed, but at the cost of their overall effectiveness. If more regulatory and cultural functions had been considered, such as support for invertebrate biodiversity, and/or a more

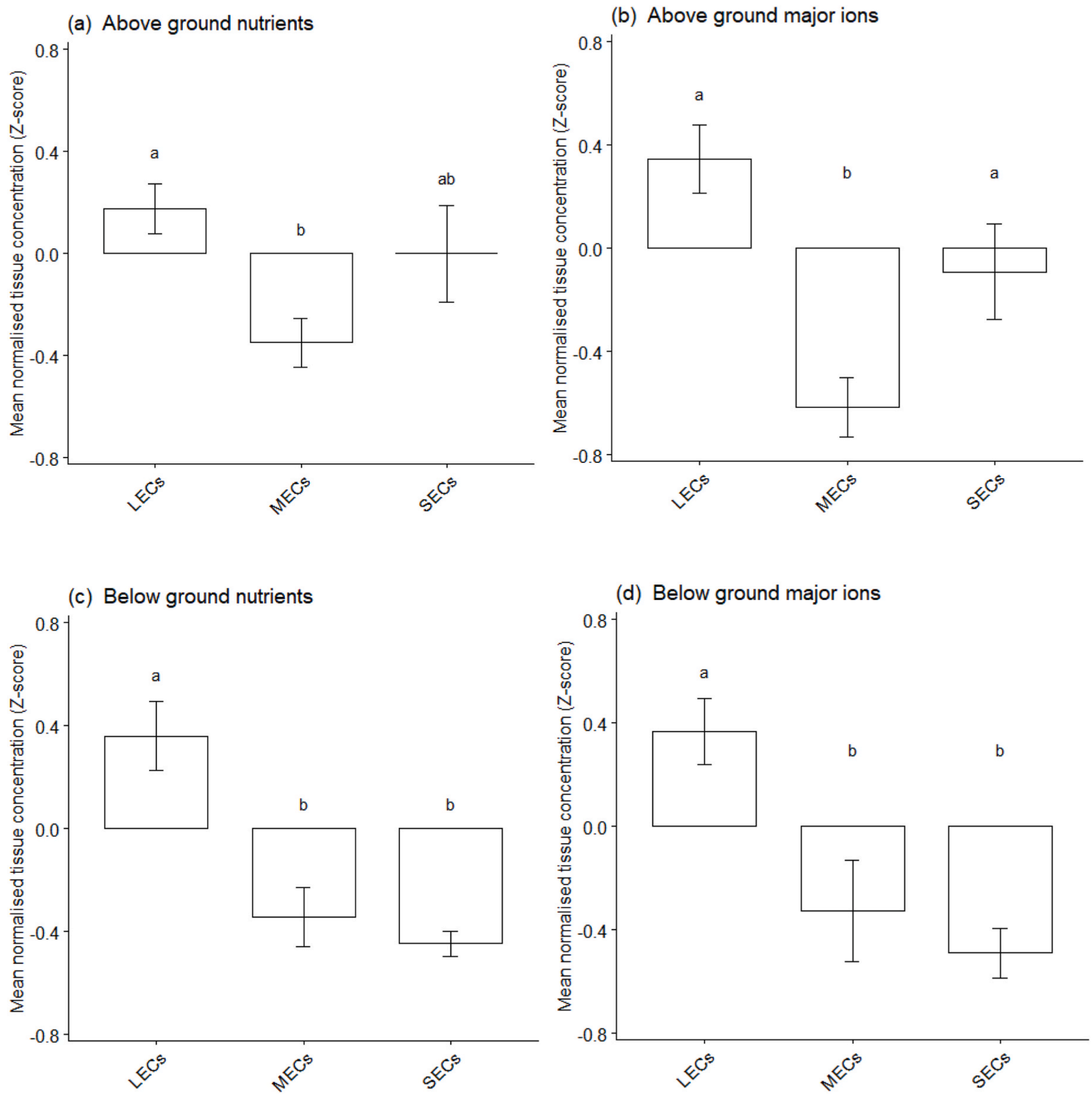

Fig. 3. Mean normalised above-ground (a, b) and below-ground tissue concentrations (c, d) (normalised by z-scores) for large statured emergent communities (LECs) ($n = 28$), Mixed statured communities (MECs) ($n = 8$) and small statured communities (SECs) ($n = 8$) for nutrients and major ions at the end of the experiment. Error bars show the standard error of the mean, and bars with different letters are significantly different from each other ($P < 0.05$).

comprehensive assessment of cultural value, then these types of functions may perform at higher threshold levels allowing EM to remain higher in LECs. The same patterns were mirrored in the phytoremediation objective despite Removal Efficiency (RE) being weighted strongly. However, the lack of a difference in the RE of major ions, above ground biomass and mean normalised above-ground tissue concentrations between the LECs and SECs means that these measures, which are all important indicators of phytoremediation success, did not allow the LECs to show enhanced multifunctionality at a higher performance threshold. This was despite the significantly higher below-ground biomass observed in the LECs which we expected to enhance RE. Under the regulating and cultural services objective, SECs maintained the highest level of multifunctionality throughout all performance levels, most likely due to the importance of flower production. Despite containing plants with traits from both LECs and SECs, structuring plant communities as MECs did not lead to enhanced ecosystem functioning and suggested that combining extremes of plant stature negatively impacts on ecosystem functioning and may represent a ‘worst of both worlds’ strategy.

LECs that are comprised of multiple species demonstrated higher levels of multifunctionality at low-medium levels compared to monocultures, due to the advantage of including species that are effective in several ecosystem functions (Riis et al., 2018) and complementarity in timing of growth that ensures functions are better delivered (Luo et al., 2023; Manolaki et al., 2020). However, as the performance threshold became higher (75 %), the monoculture plant community (e.g., *Typha latifolia*) was most effective. It is probable that a small set of specific ecosystem functions allowed this monoculture to maintain an overall higher level of multifunctionality. The polyculture LECs were less likely to achieve the higher performance thresholds suggesting that both the stature of communities and their inherent diversity is important. In contrast, for SECs the more species diverse community had higher levels of multifunctionality than the associated monoculture in the same group. This was mainly due to the more diverse community having species that produced conspicuous multi-coloured flowers, while the monoculture did not.

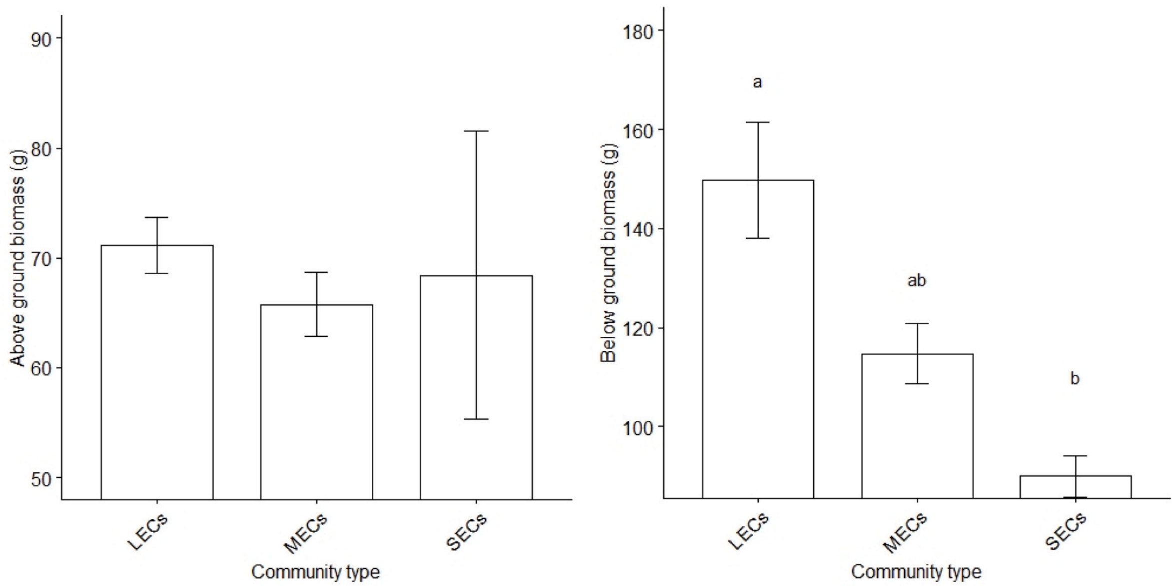

Fig. 4. Above-ground biomass and below-ground biomass of large-statured emergent communities (LECs) ($n = 28$), Mixed-statured communities (MECs) ($n = 8$), and small-statured communities (SECs) ($n = 8$), at the end of the experiment. Error bars show the standard error of the mean, and bars with different letters are significantly different from each other ($P < 0.05$).

Some of the macrophyte community types can be characterised by their ability to perform specific ecosystem functions based on their broad traits, allowing a species selection based on comparative ecology rather than species specificity. For example, the increased capacity of LECs to remove nutrients is likely related to their ability to maintain larger biomass and thus higher demand for uptake and sequestration (Brisson and Chazarenc, 2009; Vymazal, 2007). However, stature is not always an overriding factor for removal efficiency of pollutants and other species-specific physiological traits can be more important, e.g. root growth and associated biofilm attachment, and the possession of specific uptake transport proteins (Printz et al., 2016; Tanner and Headley, 2011).

Small plants in natural wetlands tend to have ruderal strategies in which rapid growth and reproduction necessitates efficient acquisition and transport of nutrients to above ground tissue (Vymazal, 2016; Willby et al., 2001). Although small statured plants can have higher pollutant tissue concentrations due to their lower biomass (i.e., less of a dilution effect), hydroponic emergent macrophyte growth in the FTWs may alter normal plant allometry, particularly for LECs, e.g., due to increased root growth at the expense of stem height and girth. It is likely that a reduction in above-ground biomass reduced the 'dilution effect' and led to the increased above-ground tissue concentration in the LECs. However, preferential storage in the roots and rhizomes of plants in LECs in preparation of overwintering also allows greater competitor and stress tolerance and can lead to higher below-ground tissue concentrations (Ge et al., 2016).

Assembling plants in mixed stature communities appears to negatively influence above-ground tissue concentrations of nutrients/major ions, likely due to antagonistic interactions between large emergent species and smaller species (Luo et al., 2023). Additionally, the water in the mesocosm containing the MECs had comparatively higher levels of dissolved oxygen suggesting lower productivity and root turnover. Despite MECs being functionally more diverse in terms of the stature trait than LECs and SECs, this did not lead to enhanced functioning, in contrast to previous studies on emergent macrophytes (Ge et al., 2015). MECs were generally intermediate in their ecosystem functioning capacity which suggests that the traits contributing most to performance in LECs and SECs types become proportionally reduced when intermixed. Although this study did not explicitly explore the effects of individual species, our results suggest that the mass ratio hypothesis (Garnier et al., 2016) is probably more important for understanding how ecosystem functioning is affected by the inclusion of species with differing traits in a community (Mokany et al., 2008).

This study has clear practical implications for the design of macrophyte communities employed for freshwater phytoremediation, particularly on FTWs. Assembling mixed communities by stature can enable practitioners to gain non-species dependent transferable knowledge on expected performance of each community type. This provides opportunities to use native flora and potentially reduce costs by transplanting local species into FTWs or propagating from existing stands of common and widespread species (Fletcher et al., 2023). While using stature as a trait provides an opportunity to generalise performance expectations, it is not advocated to abandon selection of specific species where there are very targeted project aims, for example, where the removal of a single pollutant is required. Maximising EM at a high-performance level means that environmental managers should also consider trade-offs that might occur with other services. Therefore, the restoration objectives should be clear from the outset as to which, how many, and what levels of performance, are expected from the different services derived from a phytoremediation installation. FTWs have the highest overall EM where performance is at low to medium levels, and while this suggests that phytoremediation has the capacity to be a 'multi-tool' application it also underscores that expectations must be proportionate and contextualised to the specific restoration project.

The variable performance of MECs compared to other community types highlights the importance of community assembly and of understanding how different plant combinations can influence performance (Fletcher et al., 2023). Conversely, assembling similar functional types may later lead to interspecific competition for resources (Cadotte, 2017). However, selecting species that are functionally diverse, e.g., in root zone morphology or phenology, may promote niche partitioning and thereby overall performance. Therefore, at the level of plant stature, competition and antagonistic interactions are not necessarily inevitable. Finally, this study has not explicitly considered the effect of negative outcomes from functions interacting in the EM measure. For example, the harvesting of biomass for provisioning services or pollutant export (Quilliam et al., 2015) may impact on the delivery of other services such as RE or future tissue concentration gains. Therefore, considering trade-off measures would be a useful avenue for further study in order to acquire a more complete view of the interactions between each

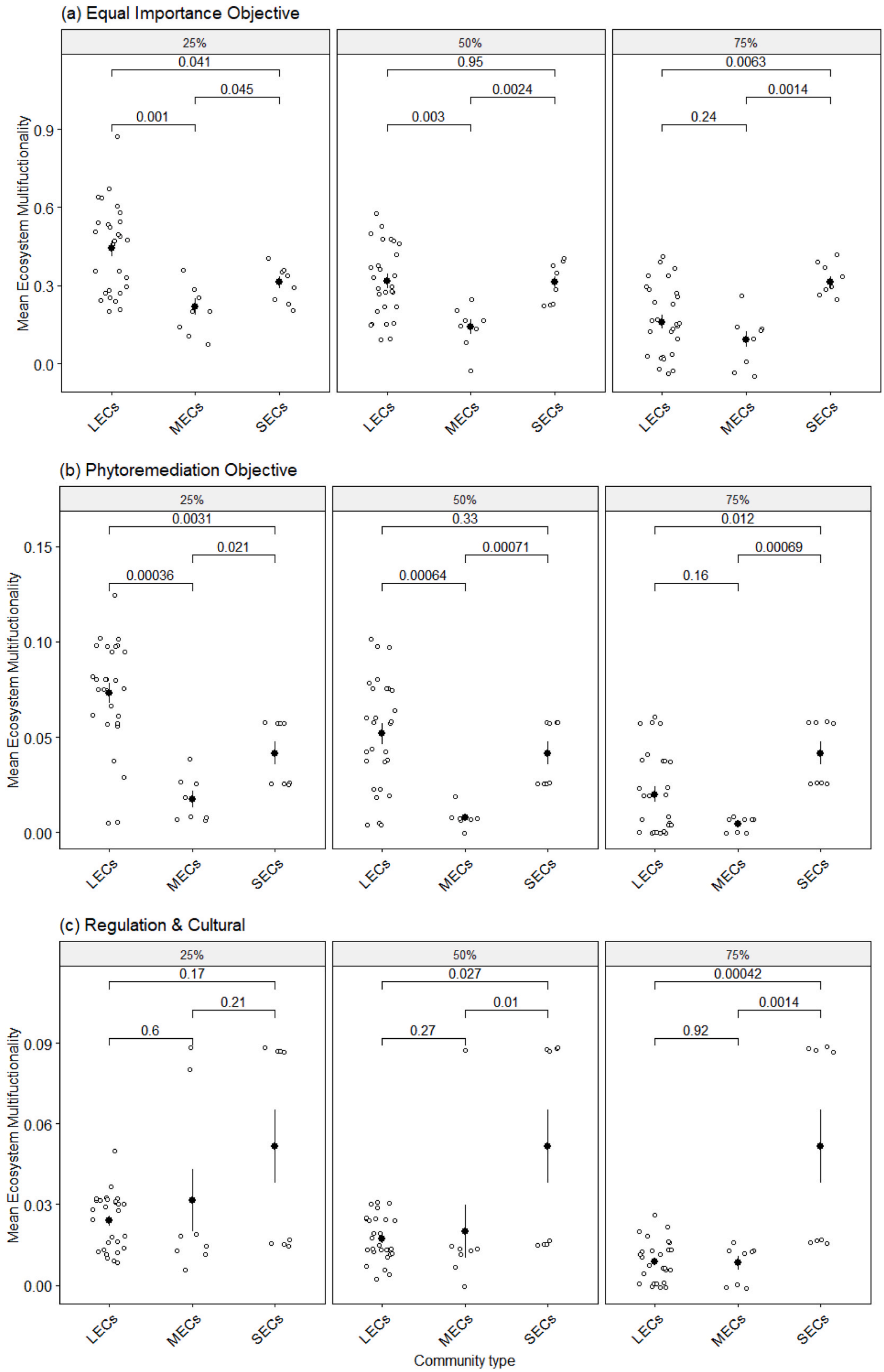

Fig. 5. Mean ecosystem multifunctionality calculated by different objectives (equal importance, phytoremediation, and regulation and supporting) for LECs ($n = 28$), MECs ($n = 8$) and SECs ($n = 8$). Each objective is split by ecosystem performance thresholds of 25 %, 50 % and 75 % of the maximum of each service. Unfilled circles represent spread of data, filled circles with error bars show the mean ±1SE. Post-hoc pairwise comparisons with P value are shown in lines between each treatment comparison.

ecosystem service The methodology employed in this study provides the framework for quantifying the different trade-offs and their impacts on multifunctionality.

5. Conclusion

Combining concepts of comparative ecology and ecosystem multifunctionality is an effective approach for determining how macrophyte communities can be assembled for optimal performance in FTWs. By focusing on the key plant trait of stature, environmental managers can more easily align objectives for freshwater restoration with plant selection as some key ecosystem functions are more likely to be associated with a particular functional community type. For the removal of nutrients from water, LECs may be more suitable than other community types, while SECs are likely to be appropriate when increased, multicoloured flower production for pollination and aesthetic value is desired. Furthermore, ecosystem multifunctionality is likely to be maintained at a higher threshold when the community performs more diverse functions, in this case the SECs. However, within the context of phytoremediation, multifunctionality is higher where the expected performance of functions is lower, which means environmental managers must recognise a potential trade-off between these outcomes. In other words, there is greater confidence of effective pollutant removal and less confidence of multiple functions including pollutant removal with increased performance expectations. There is clear potential for aquatic phytoremediation to be a 'multi-tool' in the freshwater restoration tool kit; combining measures of ecosystem multifunctionality and plant community assembly provides a framework for enhancing the value of FTW systems as a nature-based solution.

CRediT authorship contribution statement

Jonathan Fletcher: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Nigel Willby:** Conceptualization, Writing - review & editing. **David Oliver:** Writing - review & editing. **Richard S. Quilliam:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Funding for this work was provided by the Scottish Government Hydro Nation Scholars Programme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117818.

References

Allan, E., Manning, P., Alt, F., Binkenstein, J., Blaser, S., Blüthgen, N., Böhm, S., Grassein, F., Hölzel, N., Klaus, V.H., Kleinebecker, T., 2015. Land use intensification alters ecosystem multifunctionality via loss of biodiversity and changes to functional composition. Ecol. Lett. 18, 834–843.

Berger, E., Haase, P., Kuemmerlen, M., Leps, M., Schaefer, R.B., Sundermann, A., 2017. Water quality variables and pollution sources shaping stream macroinvertebrate communities. Sci. Total Environ. 587, 1–10.

Birk, S., Chapman, D., Carvalho, L., Spears, B.M., Andersen, H.E., Argillier, C., Auer, S., Baattrup-Pedersen, A., Banin, L., Beklioğlu, M., Bondar-Kunze, E., 2020. Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. Nat. Ecol. Evol. 4, 1060–1068.

Brisson, J., Chazarenc, F., 2009. Maximizing pollutant removal in constructed wetlands: should we pay more attention to macrophyte species selection? Sci. Total Environ. 407, 3923–3930.

Butterfield, B.J., Suding, K.N., 2013. Single-trait functional indices outperform multi-trait indices in linking environmental gradients and ecosystem services in a complex landscape. J. Ecol. 101, 9–17.

Cadotte, M.W., 2017. Functional traits explain ecosystem function through opposing mechanisms. Ecol. Lett. 20, 989–996.

Carrillo, V., Casas-Ledón, Y., Neumann, P., Vidal, G., 2023. Environmental performance of constructed wetland planted with monocultures and polycultures for wastewater treatment. Ecol. Eng. 193, 107015.

Chen, Z., Cuervo, D.P., Müller, J.A., Wiessner, A., Köser, H., Vymazal, J., Kästner, M., Kuschk, P., 2016. Hydroponic root mats for wastewater treatment—a review. Environ. Sci. Pollut. Control Ser. 23, 15911–15928.

Colares, G.S., Dell'Osbel, N., Wiesel, P.G., Oliveira, G.A., Lemos, P.H.Z., da Silva, F.P., Lutterbeck, C.A., Kist, L.T., Machado, Ê.L., 2020. Floating treatment wetlands: a review and bibliometric analysis. Sci. Total Environ. 714, 136776.

Daam, M.A., Teixeira, H., Lillebø, A.I., Nogueira, A.J., 2019. Establishing causal links between aquatic biodiversity and ecosystem functioning: status and research needs. Sci. Total Environ. 656, 1145–1156.

Dinno, A., 2017. dunn.test: Dunn's test of multiple comparisons using rank Sums. R Package Version 1.3.5.

Fletcher, J., Willby, N.J., Oliver, D.M., Quilliam, R.S., 2020. Phytoremediation using aquatic plants. In: Shmaefsky, B.R. (Ed.), Phytoremediation – *In-Situ* Applications (Advanced Concepts & Strategies in Plant Sciences). Springer Nature, pp. 205–260. ISBN978-3-030-00099-8.

Fletcher, J., Willby, N., Oliver, D.M., Quilliam, R.S., 2022. Resource recovery and freshwater ecosystem restoration – prospecting for phytoremediation potential in wild macrophyte stands. Resourc. Environ. Sustain. 7, 100050.

Fletcher, J., Willby, N., Oliver, D.M., Quilliam, R.S., 2023. Field-Scale floating treatment wetlands: quantifying ecosystem service provision from monoculture vs. Polyculture macrophyte communities. Land 12, 1382.

Garnier, E., Navas, M.L., Grigulis, K., 2016. Plant traits and ecosystem properties. In: Plant Functional Diversity: Organism Traits, Community Structure, and Ecosystem Properties, online edition. Oxford Academic (Chapter 6).

Ge, Y., Han, W., Huang, C., Wang, H., Liu, D., Chang, S.X., Gu, B., Zhang, C., Gu, B., Fan, X., Du, Y., 2015. Positive effects of plant diversity on nitrogen removal in microcosms of constructed wetlands with high ammonium loading. Ecol. Eng. 82, 614–623.

Ge, Z., Feng, C., Wang, X., Zhang, J., 2016. Seasonal applicability of three vegetation constructed floating treatment wetlands for nutrient removal and harvesting strategy in urban stormwater retention ponds. Int. Biodeterior. Biodegrad. 112, 80–87.

Geng, Y., Han, W., Yu, C., Jiang, Q., Wu, J., Chang, J., Ge, Y., 2017. Effect of plant diversity on phosphorus removal in hydroponic microcosms simulating floating constructed wetlands. Ecol. Eng. 107, 110–119.

Haines-Young, R., Potschin, M., 2018. Common international classification of ecosystem services (CICES) V5.1 guidance on the application of the revised structure. Barton Fabis. Available at: www.cices.eu.

Han, W., Ge, Y., Ren, Y., Luo, B., Du, Y., Chang, J., Wu, J., 2018. Removal of metals and their pools in plant in response to plant diversity in microcosms of floating constructed wetlands. Ecol. Eng. 113, 65–73.

Hoagland, D.R., Arnon, D.I., 1950. The water-culture method for growing plants without soil. Circ. Calif. Agric. Exp. Stn. 347, 1–32.

Jones, T.G., Willis, N., Gough, R., Freeman, C., 2017. An experimental use of floating treatment wetlands (FTWs) to reduce phytoplankton growth in freshwaters. Ecol. Eng. 99, 316–323.

Lavorel, S., Grigulis, K., 2012. How fundamental plant functional trait relationships scale-up to trade-offs and synergies in ecosystem services. J. Ecol. 100, 128–140.

Luo, Y., Chen, Q., Liu, F., Dai, C., 2023. Both species richness and growth forms affect nutrient removal in constructed wetlands: a mesocosm experiment. Front. Ecol. Evol. 11, 1139053.

Manolaki, P., Mouridsen, M.B., Nielsen, E., Olesen, A., Jensen, S.M., Lauridsen, T.L., Baattrup-Pedersen, A., Sorrell, B.K., Riis, T., 2020. A comparison of nutrient uptake efficiency and growth rate between different macrophyte growth forms. J. Environ. Manag. 274, 111181.

Mokany, K., Ash, J., Roxburgh, S., 2008. Functional identity is more important than diversity in influencing ecosystem processes in a temperate native grassland. J. Ecol. 96, 884–893.

Pavlineri, N., Skoulikidis, N.T., Tsihrintzis, V.A., 2017. Constructed Floating Wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chem. Eng. J. 308, 1120–1132.

Printz, B., Lutts, S., Hausman, J.F., Sergeant, K., 2016. Copper trafficking in plants and its implication on cell wall dynamics. Front. Plant Sci. 7, 601.

Quilliam, R.S., van Niekerk, M.A., Chadwick, D.R., Cross, P., Hanley, N., Jones, D.L., Vinten, A.J., Willby, N., Oliver, D.M., 2015. Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land? J. Environ. Manag. 152, 210–217.

R Core Team, 2019. R: A Language and Environment for Statistical Computing. R. Vienna: Foundation for Statistical Computing. Available at: https://www.r-project.org/.

Riis, T., Olesen, A., Jensen, S.M., Alnoee, A.B., Baattrup-Pedersen, A., Lauridsen, T.L., Sorrell, B.K., 2018. Submerged freshwater plant communities do not show species complementarity effect in wetland mesocosms. Biol. Lett. 14, 20180635.

Sakakibara, M., Ohmori, Y., Ha, N.T.H., Sano, S., Sera, K., 2011. Phytoremediation of heavy metal-contaminated water and sediment by *Eleocharis acicularis*. CLEAN–Soil, Air, Water 39, 735–741.

SEAL Analytical (no date) AutoAnalyzer Multi-test Methods. Available at: https://www.seal-analytical.com/Methods/AutoAnalyzerMethods/AutoAnalyzerMulti-testMethods/tabid/80/language/en-US/Default.aspx (Accessed: 8 September 2019).

Tanner, C., Headley, T.R., 2011. Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. Ecol. Eng. 37, 474–486.

van Rees, C.B., Jumani, S., Abera, L., Rack, L., McKay, S.K., Wenger, S.J., 2023. The potential for nature-based solutions to combat the freshwater biodiversity crisis. PLOS Water 2, e0000126.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Sci. Total Environ. 380, 48–65.

Vymazal, J., 2016. Concentration is not enough to evaluate accumulation of heavy metals and nutrients in plants. Sci. Total Environ. 544, 495–498.

Wang, Q., Cui, Y., Dong, Y., 2002. Phytoremediation of polluted waters potentials and prospects of wetland plants. Acta Biotechnol. 22, 199–208.

Wang, C.Y., Sample, D.J., Day, S.D., Grizzard, T.J., 2015. Floating treatment wetland nutrient removal through vegetation harvest and observations from a field study. Ecol. Eng. 78, 15–26.

Willby, N.J., Pulford, I.D., Flowers, T.H., 2001. Tissue nutrient signatures predict herbaceous-wetland community responses to nutrient availability. New Phytol. 152, 463–481.