Floating Islands as a Tool to Promote Biodiversity in Pit Lakes

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Abstract

Closure of pit lakes as aquatic ecosystems is viable, sustainable and economically responsible. Riparian vegetation and littoral areas are critical ecosystem components that cannot be established before the lake is full. Pilot-scale vegetated artificial floating islands were deployed in two moderately saline Australian pit lakes (≈5-12 mS cm^{-1}) to determine their impacts on biodiversity. Two of four plant species on the AFIs grew successfully and AFIs supported terrestrial (birds) and aquatic biodiversity (macroinvertebrates and fish). AFIs had higher sedimentation rates than lake controls. A larger-scale trial with >100 m^2 AFIs has begun incorporating lessons from this proof-of-concept pilot.

Keywords: Riparian vegetation, mine closure, birds, fish, macroinvertebrates, sedimentation

Introduction

Natural floating islands of fringing vegetation occur in many lakes globally (e.g., Inle Lake, Myanmar, Oo *et al.* 2022); they increase coverage and biodiversity of emergent plants, are resilient to water level changes, act as seed banks, and create habitat for terrestrial and aquatic animals (John *et al.* 2009). Artificial floating islands (AFIs) replicate aspects of natural floating islands, usually with artificial buoyancy and no (or limited) soil to support plants (Yeh *et al.* 2015).

Closure of pit lakes as aquatic ecosystems (see Lund and Blanchette 2023) is underpinned by the biodiversity stimulated by riparian vegetation and nutrients (Blanchette and Lund 2021). Surface contouring and revegetation is typically completed prior to filling which often takes many years (or decades) to complete. Riparian zones require proximity to the water to survive and therefore cannot be established until the lake has filled, creating a long period where the aquatic ecosystem is unlikely to meet regulator and public expectations.

As commercial AFIs have primarily been used to remove nutrients in wetlands (Stewart *et al.* 2008), AFIs in pit lakes appears initially counterintuitive to solving the problems of low nutrient levels in pit lakes. However, AFIs may provide an ongoing source of plant propagules to seed the lakes' edges during- and post-filling. Pit lake sediments typically contain very low levels of carbon (Lund *et al.* 2020) and adding C via biofilm sloughs, dead leaves, and roots from the AFIs can improve biodiversity and sediment biogenic processes (Lund and McCullough 2015).

The aim of this study was to investigate the use of pilot-scale AFIs as a proof-of-concept in saline pit lakes using both quantitative and qualitative (observational) data. Our research question was: can AFIs be successfully deployed in pit lakes, and could they enhance biodiversity? Using treatment and control AFIs, we measured: plant growth characteristics, sedimentation and C content (quantitative), and observed biodiversity (bird use, macroinvertebrates, and fish).

Methods

Study lakes and experimental design

Study coal mine pit lakes (n= 2, Lakes 'BL2' and 'BL4') were situated in the Bowen Basin (Queensland, Australia), which is Köppen-Geiger climate classification BSh (arid steppe climate with hot summers and predominantly summer rainfall (Peel *et al.* 2007)). Lake BL4

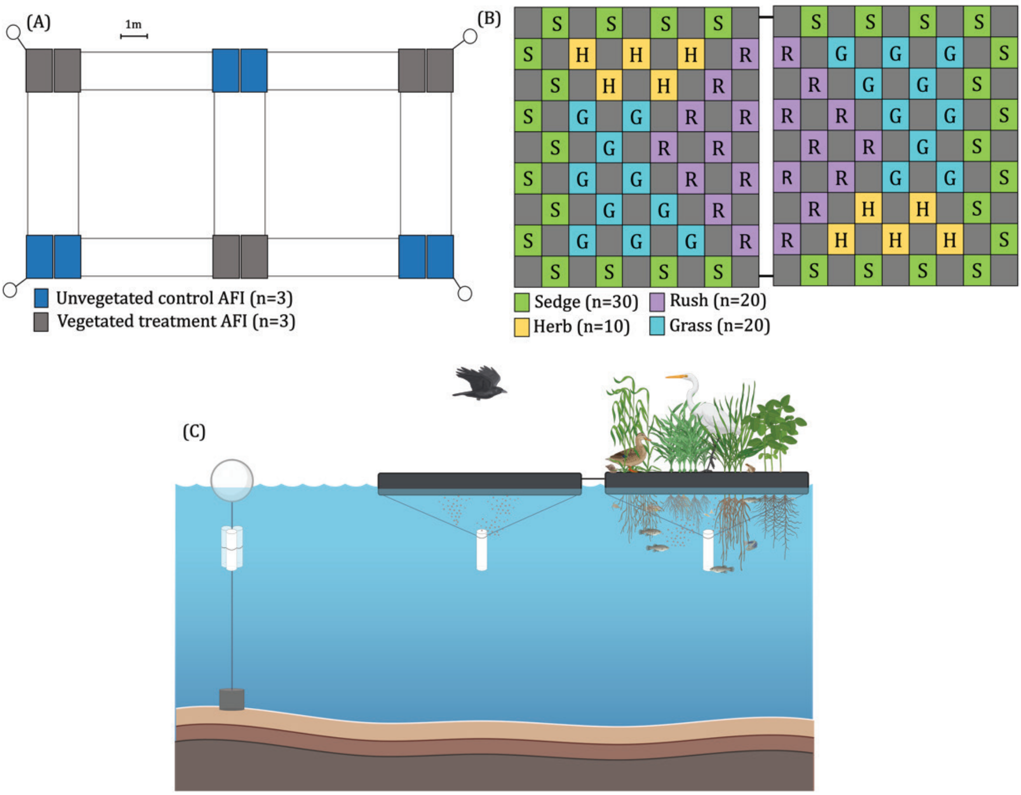

Figure 1 *Schematic representation of the **(A)** AFIs set up and **(B)** plant distribution map on the vegetated treatment AFI. Each vegetated AFI was made of 2 modules separated by 5 m (each module: 1 m x 1.5 m) with 80 plants from 4 species: P. decipiens ('herb'), L. hexandra ('grass'), J. usitatus ('rush'), and F. ferruginea ('sedge'). **(C)** Sediment traps were installed ≈1 m under each AFI and as a control in the lakes' open waters (image created with BioRender.com).*

was moderately saline (≈12 mS cm^{-1}), ≈15 m deep and 10.5 ha. Lake BL2 was smaller (2.6 ha) brackish (≈5 mS cm^{-1}), and ≈12 m deep (see Blanchette and Lund 2021 for more on lakes). As of the time of this study (December 2022– April 2024), the lakes had not undergone any rehabilitation.

AFIs were installed in both lakes in December 2022. The overall construction was 6 small (3 m^2) AFIs (3 'vegetated' treatments, 3 'unvegetated' controls, arranged in a randomised block design; Fig. 1a). Each AFI consisted of 2 closely connected modules separated by 5 m (each module: 1 m x 1.5 m, polyethylene closed cell foam ≈10 mm sheets with 40 plant pots (1 plant per pot, bedded in with coir) suspended through holes in each sheet, Water Quality Solutions, Melbourne, Australia). Each vegetated AFI had 80 young plants of Australian taxa frequently used in wetland restoration projects (Barrett 2013): *Persicaria decipiens* ('slender knotweed - grass'; n= 10), *Leersia hexandra* ('swamp rice grass'; n= 20), *Juncus usitatus* ('common rush'; n= 20), and *Fimbristylis ferruginea* ('rusty sedge'; n= 30) (Fig. 1b).

In June 2023, dead plants or empty pots were replaced with the same species and sediment traps were installed. One sediment trap (0.5 m x 0.086 m int. dia. PVC tube, capped at the bottom, 2.90 L) was suspended ≈1 m beneath each AFI (n= 6) to capture fallout from islands and avoid other lake sedimentation processes. Control traps (n= 3) were deployed ≈10 m from the AFIs (≈1 m deep) held taught between a 20 kg concrete weight and a buoy (Fig. 1c).

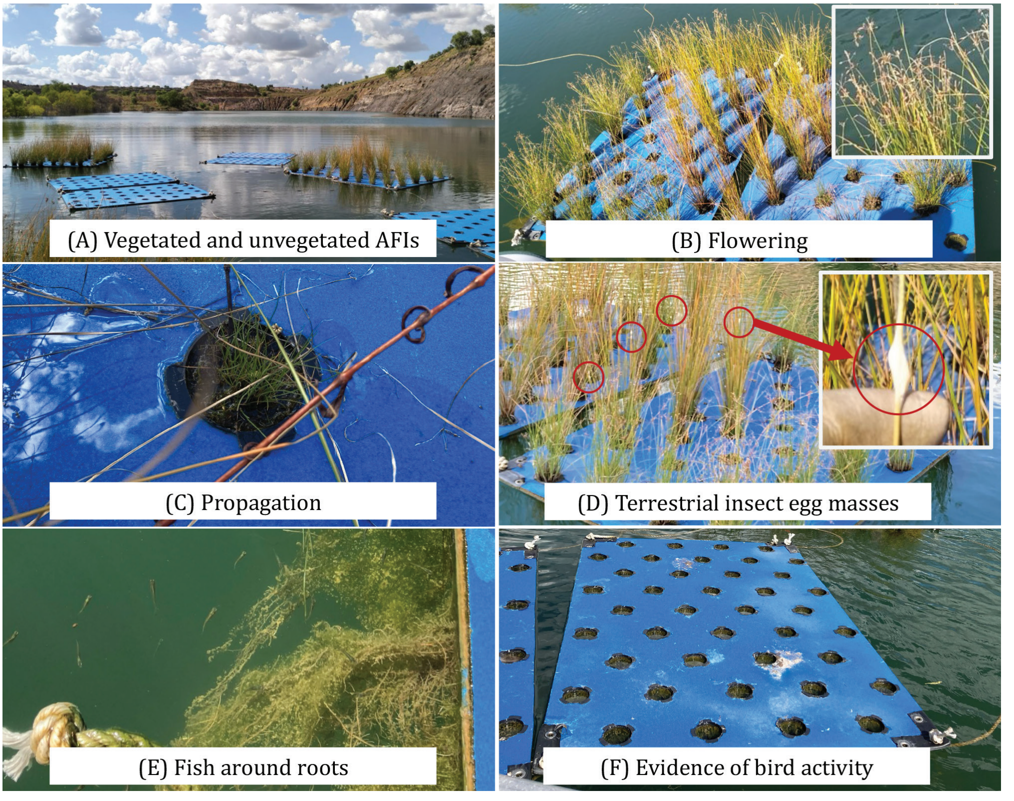

***Figure 2** Photographs of (A) 'vegetated' treatment and 'unvegetated' control AFIs installed at BL2; **(B)** Evidence of flowering; **(C)** propagation; **(D)** terrestrial insect egg masses (highlighted in circles); **(E)** fish around roots; and **(F)** evidence of bird activity.*

Data collection – plants, sediment, macroinvertebrates

The overall plant collection methodology was two sampling events per lake (June 2023 (both lakes), November 2023 (BL2) and April 2024 (BL4)). During each sampling event, 3 random pots containing surviving plants, per species (n= 2) were harvested from each vegetated AFI. Plants were frozen and later in the laboratory were rinsed with water to remove the soil and invertebrates. Invertebrates were preserved in 70% ethanol and identified to family or higher level. For each plant sample, the number of inflorescences, maximum length of roots, length of stems, and the number of stems were quantified. Plants were then separated into above- (stems) and below- (roots and rhizomes) ground biomass. All stems (living or dead) were counted together, as all stems were considered alive in June 2023. Biomass was measured after the plant tissue was dried in an oven at 80 °C for a minimum of 48 h until a constant weight was reached.

Sediment traps were retrieved April 2024 at BL4, and November 2023 at BL2. Upon collection, clear water was decanted from the tubes, the remaining water was shaken to homogenise and then filtered (pre-weighed 1.2 µm Glass Fibre filters (GFF), Whatman) until clogged, and the volume filtered was recorded. Filters were frozen (-20 °C) before being dried at 104 °C ± 1° C for at least 1.5 h until constant weight was achieved and sedimentation rate determined. Filters were then burnt at 500 °C for 4 h to allow determination of loss on ignition (LOI) as measure of organic matter content. Carbon content was calculated by dividing the LOI by 2 as per Pribyl (2010).

Data analyses – plant material and sediment

Plant growth data (root maximum length, mean stem length, mean number of stems, Above- and below- ground biomass, and number of inflorescences) for *J. usitatus* and *F. ferruginea* were normalised and Euclidean distance used to generate a resemblance matrix. A three-way PERMANOVA (9999 permutations; significance $p<0.05$), comparing fixed factors, 'species', 'lake' and 'date' (November 2023 and April 2024 were treated as the same time period) (Primer v7, Primer-e, New Zealand) was used to test the null hypothesis that the growth of plants was similar between species, lakes and over time. Pearson correlation coefficients were calculated between all parameters and significance tested.

The null hypotheses that sedimentation rates were not influenced by planting or lake was tested with a two-way ANOVA, with fixed factors of 'treatment' (AFI control, AFI vegetated) and 'lake' (BL2, BL4) were used to test for differences in sedimentation rates (1/x transformation) and LOI, using SPSS v29 (IBM, New York). Tukey's post hoc test was used to explore significant results.

Results and Discussion

Plant survival rates, growth and flowering

During the 12–16-month experiment at both lakes, most planted specimens of *J. usitatus* and *F. ferruginea* survived and flourished, whereas *P. decipiens* died, even after replanting with stronger specimens (Fig. 2a-c). *L. hexandra* initially died at all sites, however after replanting with better stock, 58% of specimens survived in BL2 until the end of the experiment, with none surviving at BL4. Plant survival was affected by initially small, poorly developed specimens for *P. decipiens* and *L. hexandra*, rapid change in salinity from the nursery (<1 mS cm^{-1}) to the lakes without acclimation, and excessive wave action at the anchor points, which was corrected using buoys in June 2023. Many of the empty pots were successfully colonised by propagules from mainly *F. ferruginea* (Fig. 2c).

Plant parameters were significantly different ($p<0.05$) between lakes, species, and dates, however as all interactions were also significant ($p<0.05$) the test was invalid and the relationships between the factors were investigated using PCA (Fig. 3). In *F. ferruginea* above- and below- ground biomass was positively correlated to stem count ($r= 0.98$ and $r= 0.74$ respectively; $p<0.05$), to each other ($r= 0.78$; $p<0.05$) and to inflorescences ($r= 0.91$ and $r= 0.83$ respectively; $p<0.05$). Stem length was correlated to below ground biomass ($r= -0.5$; $p<0.05$) and inflorescences ($r= 0.56$; $p<0.05$). Stem count was correlated to inflorescences ($r= 0.87$; $p<0.05$). In contrast, with *J. usitatus,* only above-ground biomass was positively correlated to stem count ($r= 0.86$; $p<0.05$) and below ground biomass was weakly correlated to maximum root length ($r= 0.55$; $p<0.05$).

In the first 6 months after planting (June 2023), *J. usitatus* parameters were tightly clustered within and between lakes in the PCA, while *F. ferruginea* grew better (in particularly above- and below- ground biomass) in BL2 compared to BL4 (raw data not shown). After another 6-10 months, *J. usitatus* in BL2 had changed little from June 2023, while those in BL4 had increased root biomass, but fewer and shorter stems and shorter roots than in June 2023, and inflorescences had increased. In contrast, *F. ferruginea* in BL4 had increased in all parameters compared to June 2023, while in BL2 increases were seen in all parameters except for stem length and inflorescences. In summary, *J. usitatus* survived over a year in BL4, but had grown little, and in BL2 the species had grown slightly. *F. ferruginea* grew well in both lakes, but slightly better in BL4; it is likely that over time, this species would have displaced *J. usitatus* and possibly *L. hexandra* in BL2.

In sum, choosing the appropriate species for the lake salinity will be important for their overall success and it may be challenging to maintain a diverse range of plants on the islands in the long term. Excessive wave action was also an issue and should be considered in terms of plant survival.

Sedimentation

Sedimentation rate was not significantly different ($F_{1,12}= 1.3$; $p= 0.27$) between lakes but was different between treatments ($F_{2,12}= 14.7$; $p<0.01$), although the interaction was

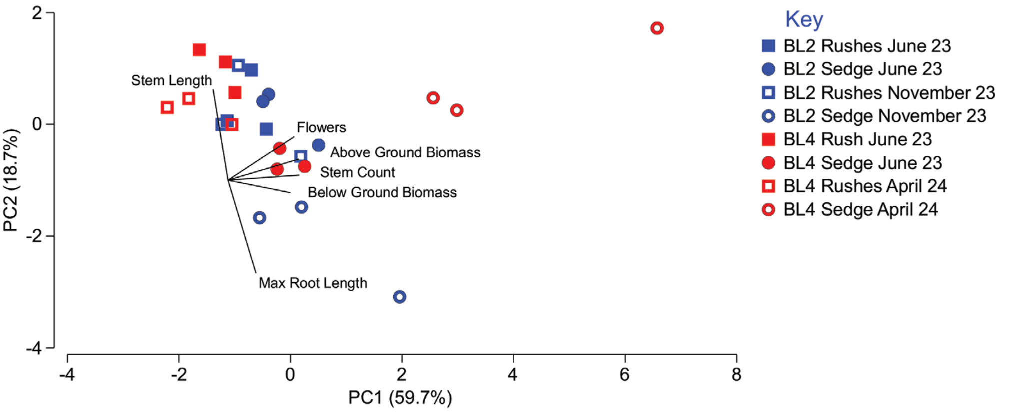

***Figure 3** PCA of average plant parameters from vegetated AFIs in BL2 and BL4 measured in June 2023 and in November 2023 or April 2024. Lines indicate positive correlations with the ordination space, with the length of the line reflecting projection into other dimensions.*

also significant ($F_{2,12}$= 7.3; p<0.01). Post hoc tests indicate that the lake sedimentation rates were lower than those from the islands, with the island treatments (AFI control, AFI treatment) were not significantly different. In BL4 the source of the high variability (coefficient of variability >82.4% compared to <33.7% in BL2) in the non-C component of the island sedimentation is not known, however the islands were located close to the old access ramp near the shore and in relatively shallow water (<3 m) which may have exposed the collection tubes to sediment resuspension caused by winds and waves or surface runoff. The sedimentation rate in lake BL2 was 3.6 ± 0.2SE g m^{-2} d^{-1} and in BL4 was 1.8 ± 0.2SE g m^{-2} d^{-1} with carbon contents of 1.9% and 3.9% respectively (Fig. 4), which was similar to those in Lake Kepwari and WO5H coal pit lakes in Collie, Western Australia (Lund *et al.* 2020; Lund *et al.* 2019).

LOI was significantly different between lakes ($F_{1,12}$= 90.7; p<0.01) and treatments ($F_{2,12}$= 11.1; P<0.01) with no significant interaction ($F_{2,12}$= 3.5; p= 0.63). Post hoc tests show the main differences were between islands and the lake and that carbon content was higher in the BL4 islands (veg.: 5.1% ± 0.1SE; control: 4.8% ± 0.1SE) compared to those in BL2 (veg.: 2.6% ± 0.2SE; control: 3.6% ± 0.4SE).

Islands appeared to promote sedimentation rates underneath them which would be a positive for the sediment development, however the sediment collected could partially have come from the soil in which the plants were planted - although as the two treatments were not statistically different this may not be an important factor.

Sediments collected from the control AFIs were characterised by a black colour and strong sulfur smell, whereas those from the vegetated AFIs were green and odourless (Fig. 4a-b). As the tubes were deployed for relatively long periods, organic breakdown may have occurred leading to an underestimation of C. The difference observed in colour and smell suggests anoxic and aerobic decomposition of organic matter occurred in the controls and vegetated islands respectively, likely due to oxygen leakage from the plant roots. The higher efficiency aerobic decomposition in the vegetated islands is likely to have resulted in greater underestimation in C content compared to the controls.

Invertebrates and birds – qualitative observations

Bird activity (no nesting) was observed via droppings (Fig. 2) on all islands (control and vegetated). Fish were observed congregating under the vegetated AFI at plant roots (Fig. 2e). Invertebrates were mainly aquatic (Dipteran larvae, Hemiptera, Odonata, Coleoptera, Gastropods), with some terrestrial Hemiptera, Coleoptera and

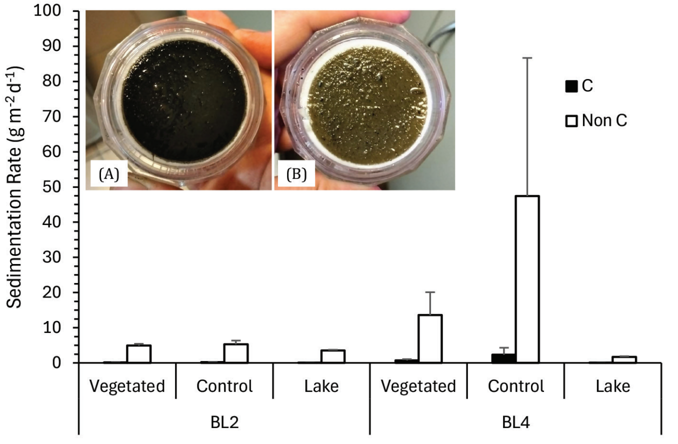

Figure 4 *Mean (± SE) sedimentation rate (g m^{-2} d^{-1}) showing proportion that was C – black bar, from sediment traps installed under the vegetated (n= 3), unvegetated control (n= 3) AFIs, and at a lake control site ≈10 m from the AFIs (n= 3) at BL2 and BL4. Photographs of filters from control* ***(A)****, and vegetated* ***(B)*** *AFIs at BL4.*

Arachnida. Invertebrate richness was similar between *F. ferruginea* and *J. usitatus*, in June 2023, although it was over twice as high in BL4 (e.g. 0.3 mean taxa richness per plant in BL2 vs 1.1 in BL4). Abundance (2 - 4.6 individuals per plant) and richness (0.7 - 1.4 taxa per plant) increased in both lakes in November 2023 and April 2024 and was slightly higher in *J. usitatus* in BL2 but lower at BL4.

Conclusions

Our research question was: can AFIs be successfully deployed in pit lakes, and do they enhance terrestrial and/or aquatic biodiversity? In this pilot study we used relatively inexpensive floating islands and four plant species to answer this question as a proof-of-concept with a mix of quantitative and qualitative (observational) data.

We successfully constructed and deployed AFIs. *F. ferruginea* thrived while *J. usitatus* survived and *L. hexandra* started to thrive in BL2 only - lake salinity and wave action were important factors in plant survival. Sedimentation rates were higher under the AFIs with higher C content in both lakes than 'lake controls.' Islands provided habitat for birds, fish, macroinvertebrates and could act as sources of plant propagules for rehabilitation of filling pit lakes. Bird usage could not only contribute to biodiversity, but also to nutrients that AFI plants may remove from the lake. In sum, AFIs offer potential for increasing biodiversity in pit lakes, with the greatest benefits in the littoral zone due to lake depth. The success of this pilot study has allowed us to commence a full-scale trial using more substantial (>100 m^2) islands. The upscale will consider the importance of lake water chemistry to plant survival, use camera traps to quantify bird activity, and employ tools like environmental DNA and macroinvertebrate sampling to evaluate the islands' contribution to increasing biodiversity.

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