RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

RECOAST: RECYCLING FOR RESTORATION

RESEARCH ARTICLE

Wetland plant growth in recycled glass sand versus dredged river sand: evaluating a new resource for coastal restoration

Elizabeth H. MacDougal[1,2], Bek X. L. Markel[1], Emily C. Farrer[1], Shehbaz Ahmad[1], Julie N. L. Albert[1], Sunshine A. Van Bael[1]

Sand made from recycled glass cullet could supplement limited dredged river sand (dredge) in coastal wetland restorations; however, its suitability for wetland plants is unknown. In two experiments, we compared the biomass of several wetland plants in recycled glass sand to growth in dredge. First, we grew *Salix nigra*, *Zizaniopsis miliacea*, and *Sporobolus alterniflorus* in fine- and coarse-glass sands, dredge, and a coarse-glass/dredge mixture. Second, we grew *Taxodium distichum* and *Schoenoplectus californicus* in a revised coarse-glass blend, dredge, and a mix. We characterized the substrate porosity, particle density, and bulk density for both experiments and tested how substrate nutrients, metals, and pH impacted *S. californicus* leaf contents. We found species-specific responses to substrates: herbaceous species grew better in the mix and dredge than in glass alone, whereas trees grew equally well in the coarse glass, mix, and dredge. Glass sand was less dense than dredge. When saturated and compressed, finer-grained glass sand and mixes had lower estimated porosities than coarser glass sand and dredge. *S. californicus* leaf chemistry resembled that of the plant's substrate. This study demonstrated that wetland plants can grow in glass sand, that mixtures of glass and dredge have species-specific effects, and that substrate structure and chemistry could help explain these differences. Thus, it opens the door for broader field studies on how glass sand can best be used in coastal restoration efforts.

Key words: glass cullet, land loss, nutrients, resilience, soil, sustainability

Implications for Practice

- Physical and chemical differences between glass sand and dredged sand make glass sand an excellent candidate for use in Adaptive Restoration.
- Mixing recycled glass sand with dredged sand may support a broader range of species than using recycled glass sand or dredged sand alone.
- Using all-glass sand in a wetland restoration may favor thicker-rooted species.
- Bulk density may not be a reliable proxy for penetrability when comparing glass and dredge wetlands.
- Given the alkalinity of glass sand, monitoring for pH and redox conditions within glass sand systems may be beneficial.

Introduction

Globally, coastal wetlands are in decline: over the past two decades, a net 4,000 km^2 have been lost (Murray et al. 2022). Though indirect processes such as climate change have driven large coastal wetland losses and smaller gains in the past two decades, human activities that alter or restore wetlands account for over a quarter of these changes (Murray et al. 2022). About 90% of U.S. coastal wetland loss occurs in Louisiana (Couvillion et al. 2011). The underlying causes include natural and human-induced subsidence and relative sea level rise (Dokka 2011), loss of natural sediment supply (Boesch et al. 1994), landscape alteration such as canal building (Turner 1997; Day et al. 2000), and hurricane damage (Couvillion et al. 2011). Land restoration and preservation efforts are highly supported, with a 50 billion U.S. dollar investment plan (CPRA 2023), but there is room for improvement. Large-scale efforts to restore land in this area include a sediment diversion designed to restore up to 21 miles^2 (5,439 ha)

Author contributions: SV, EF, JA, EM conceived and designed the research; EM, BM, SA performed the experiments; EM analyzed the data and wrote the manuscript; EF, SV assisted with data analysis; all reviewed and edited the manuscript.

[1]Tulane University, 6823 St Charles Ave, New Orleans, LA, U.S.A.
[2]Address correspondence to E. H. MacDougal, email emacdougal@tulane.edu

doi: 10.1111/rec.70020
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70020/suppinfo

of coastal wetlands over the next 50 years (CPRA 2023), as well as widespread land-building projects using sand dredged from local waterways (dredge) for beneficial use. The scale of land loss is massive, however, and these large endeavors cannot reach all areas: the sediment diversion is a fixed point targeting one region, and dredge availability has been a limiting factor in the Coastal Protection and Restoration Authority's operations (CPRA 2023). Sand made from recycled glass (glass sand) could provide an additional, reliable substrate supply while diverting glass from landfills. This would increase crucial gains in coastal wetlands to help offset the loss and provide a model for other regions with access to glass recycling and limited fill for restorations. This paper builds on limited ecological research of recycled glass sand to assess whether it is a viable alternative or supplement to dredge for coastal restorations. Prior research indicates that glass sand could be a promising resource to manage erosional hotspots (Makowski et al. 2011) and should be safe for marine animals such as crabs and interstitial microorganisms (Makowski & Rusenko 2007). Although dune grasses have been shown to grow well in glass sand (Makowski et al. 2013), we do not know how coastal wetland vegetation will respond. Coastal wetlands, such as marshes and cypress-tupelo swamps, are some of the habitats in southeastern Louisiana that could gain the most from a new substrate stream, due to marshes' high erosion rates (CPRA 2023), swamps' lack of riverine input (Shaffer et al. 2009), and the limited supply of dredge to rebuild or replenish them (CPRA 2023). While dune plants may be adapted to growing in sand, marsh and swamp plants grow in soils that are typically fine sand to silt and clay and are highly organic (Kulp et al. 2005; Shaffer et al. 2009; Buczkowski et al. 2020). Thus, we should not assume coastal wetland plants will respond to glass sand in the same manner as dune plants. New wetlands in Louisiana are typically constructed with dredge. To determine whether glass sand is a viable alternative for coastal wetland restoration in this region, it is important to understand how plant growth in glass sand compares to plant growth in dredge.

Although both glass sand and dredged sand are primarily silica (Ahmad et al. n.d., in review, this special collection), they are formed through different processes that likely impact their physical and chemical properties: glass sand is formed by crushing waste glass and sieving directly into different size classes, whereas dredged sand is an erosional byproduct that has had time to weather and accumulate nutrients. Soil physical and chemical properties can both impact plant biomass, studied here, as well as the very formation and function of wetlands (Jackson et al. 2019).

Many soil physical properties are interrelated: soil particle density is positively related to bulk density, and soil bulk density positively relates to soil hardness (i.e., resistance to penetration) and negatively relates to soil porosity. When soil hardness is either too low or too great, above- and belowground plant growth is inhibited (Passioura 2002). For sandy soils, lacking the relatively lighter organic matter, one concern may be that they would have a high bulk density and hardness, impeding growth. As soils bulk density increases through, for example, natural compaction, its porosity tends to decrease, reducing regions of gas exchange and niche space for microbes (Passioura 2002) and altering their enzymatic activities, which are key to nutrient cycling (Li et al. 2002). Thus, measuring porosity, particle density, and bulk density can indicate what types of challenges to root growth, microbial symbioses, and nutrient exchange plants may face in a given substrate.

Plant growth and fertility can also be negatively impacted by nutrient deficiencies (Morgan & Connolly 2013), which can arise due to the contents and chemistry of the soil. Soil-derived nutrients include macronutrients Ca, K, Mg, N, P, S, and micronutrients B, Cl, Cu, Fe, Mb, Mn, Ni, and Zn, which are typically absorbed from a soil/water solution (White & Brown 2010). If these elements are not present in the environment, a plant may become deficient. Additionally, soil pH impacts many aspects of soil biogeochemistry, including the bioavailability of nutrients (Neina 2019) and heavy metal sorption (Barrow & Whelan 1998). Even soil texture can impact nutrient availability: fine (clay) particles have a greater surface area to volume ratio and serve as cation exchange sites, which influence nutrient cycling (Tahir & Marschner 2017; Jackson et al. 2019; Wang et al. 2021). Thus, differences in soil chemistry can translate into differences in plant chemistry and thereby plant growth.

Even though substrate texture can impact a developing soil's bulk density, porosity, and chemistry, coarse sands can still support wetland plants typically found in finer soils. Many coastal communities are finding success experimenting with methods to restore or reinforce coastal habitats, creating "living shorelines" that promote coastal wetland growth with minimal engineering (Bilkovic et al. 2016). For these projects, where clean sand is often used as fill before planting, plant height and stem density do not seem to be impeded by the resulting coarse soil texture (Bilkovic et al. 2016).

We conducted two experiments to determine how the growth of coastal wetland plants native to the U.S. Gulf Coast compares between glass sand, dredged Mississippi River sand, and a mix between the two (Fig. 1). Experiment 1 served as a proof of concept for whether the plants would grow in the glass sand. It tested three key wetland species—*Salix nigra* (Black willow), *Zizaniopsis miliacea* (Giant cutgrass), and *Sporobolus alterniflorus* (formerly *Spartina alterniflora*; Smooth cordgrass)—in four different substrates: a "fine glass" blend, ranging from glass silt to very coarse glass sand; a "broad range coarse glass" blend, ranging from glass silt to glass gravel granules; a "broad range glass/dredge mix" which was a mix of broad range coarse glass and dredge; and dredge, which contained no glass and naturally ranged from silt to very fine sand. Experiment 2 revised the substrate types used from Experiment 1 to reflect current glass availability. It tested two key wetland species' growth—*Taxodium distichum* (Baldcypress) and *Shoenoplectus californicus* (Giant bulrush)—in three substrates: a "mid-range coarse glass" blend, ranging from very fine glass sand to very coarse glass sand; a "mid-range glass/dredge mix," which was a mix of mid-range coarse glass and dredge; and dredge. To complement the biomass data, both experiments tested the physical properties of each substrate, including particle density, compaction, bulk density, and porosity. Experiment 2 additionally tested for nutrients and metals within the substrate

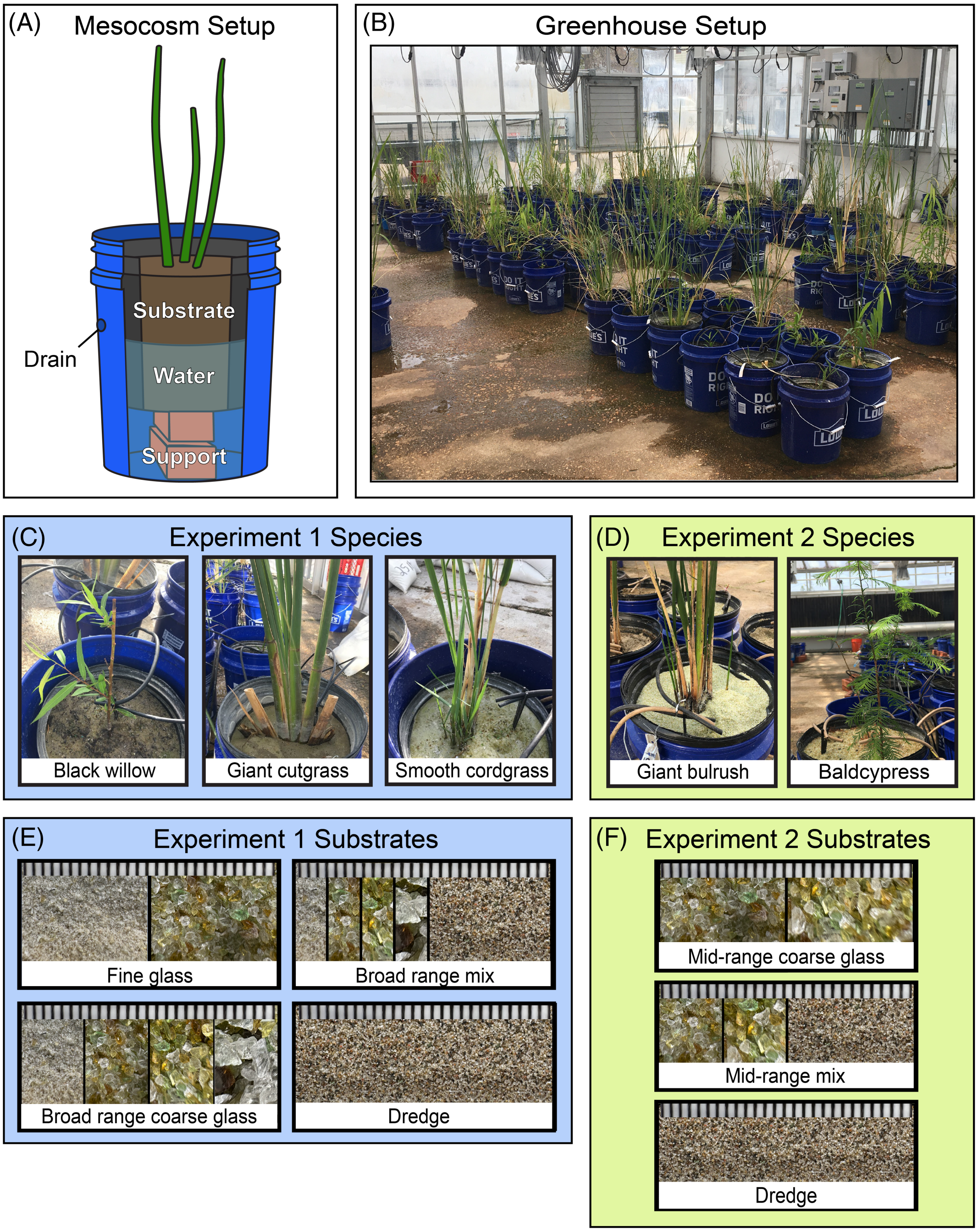

Figure 1. Visual summary of design for Experiments 1 and 2. (A) Pots were situated in outer buckets with drainage to allow for periodic flooding; (B) Experiments had a randomized, complete block design with 10 replicates of each species/substrate combination; (C and D) Experiment 1 had 3 species, and Experiment 2 had 2 species; (E and F) Experiment 1 included a fine glass and a broad range coarse glass treatment, a mix of the broad range coarse glass and dredge, and a dredge treatment, whereas Experiment 2 included a mid-range coarse glass treatment, a mix of the mid-range coarse glass and dredge, and a dredge treatment. Images of each substrate type show the relative proportions of each component. Photographs of each component were taken next to a metric ruler; the ruler in each photograph was used to scale the component images to the same reference image of a mm ruler, displayed above each set of images. Grain sizes in the images are thus scaled relative to one another.

types and the bulrush grown within them, as well as the substrate pH.

We hypothesized that substrates similar in grain size and origin to typical wetland soils of the region would best support the growth of plants adapted to those soils. Thus, we predicted the greatest biomass and key nutrient (N, P, and K) levels would be within plants grown in dredge: this substrate was fine-grained like natural marshes and swamps and came from the Mississippi

River, the original source of sediment for the Mississippi River Delta, where the study plants are native, and where the substrate would have been exposed to ambient nutrients. Furthermore, dredged sand is the standard material for restoration in the region (CPRA 2023). We predicted that for each experiment, biomass would be second greatest in the glass/dredge mix as it was comprised half of dredge, and that key nutrients would be second greatest in the plants tested in Experiment 2's glass/dredge mix. We predicted that biomass would be greater in the fine glass than in the broad range coarse glass, as the fine glass grain size range was closest to that of dredge, thus possibly more similar in grain-size related physical and chemical properties.

Methods

Experimental Methods

To determine how recycled glass sand affects vegetation growth and nutrient uptake, we conducted two full-factorial mesocosm experiments. Factors manipulated in each experiment were species and substrate type.

Biomass. Both experiments were conducted in a Tulane University greenhouse in New Orleans, LA, United States. Per experiment, we had 10 blocks, with 1 replicate of each species/substrate combination to a block (Fig. 1). Replicates were in their own pots, situated within their own buckets (Supplement S1). They were watered with deionized fresh water through an automated irrigation system, with hoses set on the substrate surface and below the pots. To simulate growing-season light levels, we set Lucalox LU1000/ECO lamps (GE Lighting, East Cleveland, OH, U.S.A.) above the plants and ran them in the morning and evening. A summary of experimental conditions is available in the Supporting Information (Table S1).

For both experiments, plant biomass was the main metric for plant growth, which required harvesting the plant to measure. To collect baseline plant size data, we measured plant height, diameter, and stem counts within 5 weeks of planting, after the plants had time to establish. The protocols for Experiment 1 baseline measurements are available in Supplement S2, and the protocols for Experiment 2 baseline measurements are available in Supplement S3. At the start of the experiment, plants within the substrates had a comparable average height, stem count, and diameter (Figs. S1 & S2).

Experiment 1. Experiment 1 was conducted from October 2021 to April 2022. It tested three species (cordgrass, cutgrass, and willow) by four substrate types (fine glass sand, broad range coarse glass sand, broad range glass/dredge mix, and dredge). There were initially 10 replicates of each treatment combination for a total of 120 pots (3 species $\times$ 4 substrate types $\times$ 10 replicates $=$ 120). The selected species are native to the U.S. Gulf Coast. More information on the species selection and planting can be found in the Supporting Information (Supplement S4).

Recycled glass sand was provided by Glass Half Full (New Orleans, LA, U.S.A.) and Mississippi River dredge was donated by Wood Materials, LLC (Harahan, LA, U.S.A.). Glass was received in bags with 4 "Levels" (L2–L5) of different sizes (Table 1). These levels were mixed in 120-lb (approximately 54.4 kg) batches in different combinations in a small cement mixer to produce each substrate (Table 1). Two weeks after planting, the plants were fertilized with 24:8:16 Miracle-Gro (Product number 302050605, Scotts Miracle-Gro Co., Marysville, OH, U.S.A.) to help them establish. Miracle-Gro was added to water in the ratio of 40 g per three gallons. Approximately 275 mL of this solution (containing around 0.23 g N and 0.077 g P) was added to each pot. They were then fertilized weekly with a solution of Miracle-Gro and $Ca(NO_3)_2$ that had a 20:1 N:P ratio, the approximate ratio of the Mississippi River's nutrients (Okwan et al. 2020). Thus, each plant received a weekly 10 mg N and 0.5 mg P.

Watering and lighting information are in Supporting Information (Supplement S5). To obtain biomass measurements, we harvested and dried the plants: we removed each plant and its root mass from the pot, rinsed the roots, and sorted through the sand to retrieve root fragments, which were included with the rest of the roots for each sample. For the cutgrass, we discarded dead shoots, which were the original shoots the plants were potted with that had browned and wilted. For the cordgrass, we included dead stems as the plants had recently flowered and begun to die back; these dead stems therefore represented new growth from the experiment. Rinsed plants were cut into aboveground (AG) and belowground (BG) portions, which were dried separately. The BG portions were subsampled for future microbiome analysis (not part of this paper), removing 5 g $\pm$ 0.5 g of the wet weight. Within 8 hours of harvest, all plants were placed in a drying oven at 72°C. Once the plants were fully dried, they were further cleaned by manually removing any substrate remaining in the root ball. The cleaned, dried plant material was then weighed to record the dry biomass for each sample.

Experiment 2. Experiment 2 was conducted from November 2022 to September 2023. It tested 2 species $\times$ 3 substrate types and initially had 10 replicates of each treatment combination for a total of 60 pots (2 species $\times$ 3 substrate types $\times$ 10 replicates $=$ 60). Two new native species were selected to broaden the scope of plants tested for compatibility with glass sand. The species selection and planting are described in the Supporting Information (Supplement S6). The bulrush plants differed in size but were arbitrarily assigned to pots to prevent biasing the data.

Experiment 2 used only one glass substrate composition, mid-range coarse glass, which did not contain the finest or coarsest particles used in Experiment 1. This was because preliminary results from Experiment 1 found that plants did not grow as well in the fine glass and because the provider's machinery changed the sizes of sand produced, making the fine glass sand less available. Substrates were mixed as in Experiment 1, though their recipes differed (Table 1).

Table 1. Grain size ranges of experimental substrates. Grain sizes were determined by Ahmad et al. (n.d., in review, this special collection).

Experiment	*Substrate*	*Components*	*Grain sizes (mm)*	*Classification (Wentworth 1922)*
1	Fine glass	50% L5 glass	0.01–0.4	Silt to sand (very fine)
		50% L4 glass	0.4–1.1	Sand (very fine) to sand (very coarse)
1	Broad range coarse glass	25% L5 glass	0.01–0.4	Silt to sand (very fine)
		25% L4 glass	0.4–1.1	Sand (very fine) to sand (very coarse)
		25% L3 glass	1.1–1.7	Sand (very coarse)
		25% L2 glass	1.7–3.4	Sand (very coarse) to gravel (granule)
1	Broad range glass/dredge mix	12.5% L5 glass	0.01–0.4	Silt to sand (very fine)
		12.5% L4 glass	0.4–1.1	Sand (very fine) to sand (very coarse)
		12.5% L3 glass	1.1–1.7	Sand (very coarse)
		12.5% L2 glass	1.7–3.4	Sand (very coarse) to gravel (granule)
		50% dredge	0.04–0.07	Silt to sand (very fine)
1, 2	Dredge	100% dredge	0.07–0.4	Silt (coarse) to sand (very fine)
2	Mid-range coarse glass	50% L4 glass	0.4–1.1	Sand (very fine) to sand (very coarse)
		50% L3 glass	1.1–1.7	Sand (very coarse)
2	Mid-range glass/dredge mix	25% L4 glass	0.4–1.1	Sand (very fine) to sand (very coarse)
		25% L3 glass	1.1–1.7	Sand (very coarse)
		50% dredge	0.07–0.4	Silt to sand (very fine)

To help the plants establish, they were fertilized 1 month after planting with 3 tsp (approximately 15 mL) of slow-release 14:14:14 Osmocote Plus (UPC 032247234528, Scotts Company, Marysville, OH, U.S.A.). These pellets were mixed into the surface substrate and watered in. Specifics on lighting and watering can be found in the Supporting Information (Supplement S7).

Harvest and biomass measurement occurred as in Experiment 1 with the following exceptions: The drying oven ranged from 67 to 71°C. The minimum number of days drying was 9. Clean plant weights collected before drying were used to correct the final dry weight, which omitted a small amount of BG tissue (up to 2.0 g) that was removed before drying. We calculated the dry weight of the removed tissue using the ratio of dry to wet BG biomass and added this to the weight of the dried sample.

Substrate Physical Properties. To identify physical differences between substrate types that might have contributed to differences in growth, we measured their dry, uncompressed porosity, particle density, and bulk density, and we estimated the bulk density, compaction, and porosity of the saturated, compressed substrate. First, the average dry, uncompressed bulk density was calculated for five replicates by taking a known mass of the dry substrate, measuring its volume in a graduated cylinder, and dividing the mass of the substrate by its volume. Then, the measured substrate was added into a graduated cylinder filled with a known quantity of water, and the volume of the sample was measured as the volume of water it displaced. The particle density was calculated as the dry substrate mass divided by the volume of the sample. Porosity was calculated by subtracting the quotient of the bulk density over the particle density from one. Thus, porosity indicates the fraction of the bulk substrate not occupied by substrate particles. Because the experiments periodically flooded the substrate, and because the substrates naturally compacted over months of watering (EM personal observation), we also calculated the saturated, compressed bulk density for five replicates of each substrate type. First, water was added to a batch of each substrate type until it was just saturated. Then, for each replicate, 10 mL of the saturated substrate was loaded into a die and compressed with an Instron 5,567 universal testing machine (Instron Corporation, Norwood, MA, USA). We used 0.48 kN of compressive force, based on the standard proctor test (Connelly et al. 2008). The final volume of saturated, compressed substrate was obtained based on the displacement in the die. Because we did not measure the dry mass of this substrate directly, we estimated the mass of the initial 10 mL substrate based on the average dry, uncompressed bulk density previously determined. We then divided this mass by the final volume in the die. This assumed that the uncompressed bulk densities of both saturated and unsaturated substrates were equivalent. For any substrates that were more tightly packed under saturated, uncompressed conditions than under dry, uncompressed conditions, the mass estimate—and thus the bulk density and compaction estimates—would have been low, and the saturated, compressed porosity estimates would have been high.

Substrate and Leaf Chemistry (Experiment 2). We submitted substrate and plant samples for nutrient and metals testing to the Soil Testing & Plant Analysis Lab (STPAL) at Louisiana State University, Baton Rouge, LA, United States. We characterized Experiment 2's initial substrate nutrients (Ca, Cu, K, Mg, Na, Ni, OM, P, S, Zn), other metals (As, Cd, Pb), and pH. For each of the three substrate types, we collected and air-dried three replicate samples (~500 mL each), for a total of nine substrate samples. For bulrush aboveground tissue, we characterized nutrients (B, Ca, C, Cu, Fe, K, Mg, Mn, N, Na, Ni, P, S, Zn) and other metals (Al, As, Cd, Mo, Pb, Se). Five bulrush replicates were arbitrarily selected from each of the three substrate treatments for a total of 15 samples. A subsample of 1.5 g of their dried AG biomass was removed for this. To do so, at least half the stems were drawn haphazardly from the bag, and 0.5–1 cm was clipped from each. They were fully ground in a sterilized coffee grinder.

Analysis

Biomass. Initial biases of plant size by treatment or block were ruled out before proceeding with the analyses. To do so, we plotted each growth metric (stem count, stem height, diameter, and condition) by each treatment and block and visually confirmed similarity.

Although 10 replicates were planned for each experiment, the final number of replicates ranged from 6 to 10. In the first experiment, there was mortality in three willow (two broad range coarse glass, and one dredge) and we donated eight surviving willow (two arbitrarily chosen from each substrate) to a community partner, meaning they were not harvested. One cutgrass died in fine glass. The remaining replicates were as follows: 8 willow in fine glass, 6 willow in broad range coarse glass, 8 willow in broad range glass/dredge mix, 7 willow in dredge, 10 cordgrass in fine glass, 10 cordgrass in broad range coarse glass, 10 cordgrass in broad range glass/dredge mix, 10 cordgrass in dredge, 9 cutgrass in fine glass, 10 cutgrass in broad range coarse glass, 10 cutgrass in broad range glass/dredge mix, and 10 cutgrass in dredge. In the second experiment, there were three mortalities: two bulrush in mid-range coarse glass and one bulrush in mid-range glass/dredge mix. Thus, there were 10 replicates as planned for Baldcypress in each substrate, but 8 bulrush in mid-range coarse glass, 9 bulrush in mid-range glass/dredge mix, and 10 bulrush in dredge.

We looked for differences in aboveground (AG), belowground (BG), and total (AG + BG) dry biomass by substrate type. All statistical analyses were performed using R Statistical Software v4.3.0 (R Core Team 2023). To account for heteroskedastic errors as needed, we used generalized least squares models to analyze the data (gls, nlme, Pinheiro & Bates 2000). We modeled the effect of species, treatment, and the interaction of both species and treatment on AG, BG, and total biomass, and included block as a main effect. To test for heterogeneous variances of biomass within species, treatment, and species-by-treatment groups, we performed a Levene's test ($\alpha < 0.05$, with the null hypothesis that all variances are equal; car, Fox et al. 2024) on each model (minus the block effect). Where the Levene's test failed ($p < 0.05$), indicating unequal variances, we included terms to correct for heterogeneous variance of species, substrate, or species and substrate, according to whichever model had the lowest AIC. We plotted the normalized residuals to visually confirm their distribution was normal and homoscedastic. Finally, we performed a type III ANOVA to assess the significance of fixed effects and determined significant differences ($\alpha < 0.05$) between treatments with a Tukey's Honest Significant Differences test (glht, multcomp, Hothorn et al. 2008).

Substrate Physical Properties. We used a simple, linear model (gls, nlme, Pinheiro & Bates 2000) to analyze the effect of substrate type on particle density, compaction, and both dry, uncompressed and saturated, compressed bulk density and porosity. Heterogeneous variance of substrate type was included in the model if it failed a Levene's Test. After validating the model by visually confirming normality and homoscedasticity of its residuals, we used a Tukey test as above to determine differences in each of the physical properties between substrate types.

Substrate and Leaf Chemistry (Experiment 2). To characterize the substrate and Giant bulrush nutrient contents, we ran Principal Component Analyses using the Redundancy Analysis function (rda, vegan, Oksanen et al. 2024). Minerals that we had tested leaves for but were not detected (As, Cd, Mo, Pb, Se) were excluded from the analysis. The remaining data were normalized to create a correlation matrix. The first two principal components were retained for analysis. Results were plotted with a biplot scaled to best represent differences between the samples, and samples were formatted to display their substrate type. To determine significant differences ($p < 0.05$) in chemical composition between substrate types for substrate and bulrush, we ran a PERMANOVA on the results of each (adonis2, vegan, Oksanen et al. 2024).

Results

Biomass

Experiment 1. Overall, plants grown in the dredge and the broad range glass/dredge mix had greater biomass than those grown in the fine glass. Plants grown in the broad range coarse glass varied in their responses: cordgrass and cutgrass had a similarly lower growth as in fine glass, but willow grew as well in the broad range coarse glass as it did in the broad range mix and the dredge (Fig. 2). The difference in how species responded is reflected in the significant interaction between species and substrates effects on AG dry biomass ($F_{6,87} = 2.4$, $p = 0.037$), BG dry biomass ($F_{6,87} = 3.6$, $p = 0.003$), and total dry biomass ($F_{6,87} = 2.7$, $p = 0.02$) (Table S2).

Experiment 2. In the second experiment, we saw a similar trend for AG biomass (Fig. 3A & 3B): the tree species selected grew equally well in the coarse glass, mix, and dredge, whereas the herbaceous species grew best in the mix and dredge and less well in the glass. However, for BG biomass (Fig. 3C & 3D) and total biomass (Fig. 3E & 3F), neither species' biomass differed by substrate type. For AG biomass, there was a main effect of substrate ($F_{2,42} = 3.3$, $p = 0.048$) and a marginally significant interaction between species and substrate ($F_{2,42} = 3.1$, $p = 0.056$). Baldcypress AG biomass was similar across substrates (Fig. 3A), whereas Bulrush AG biomass was lower in mid-range coarse glass and greater in dredge and mid-range glass/dredge mix (Fig. 3B). Neither Baldcypress nor Bulrush BG biomass was significantly affected by substrate type; there

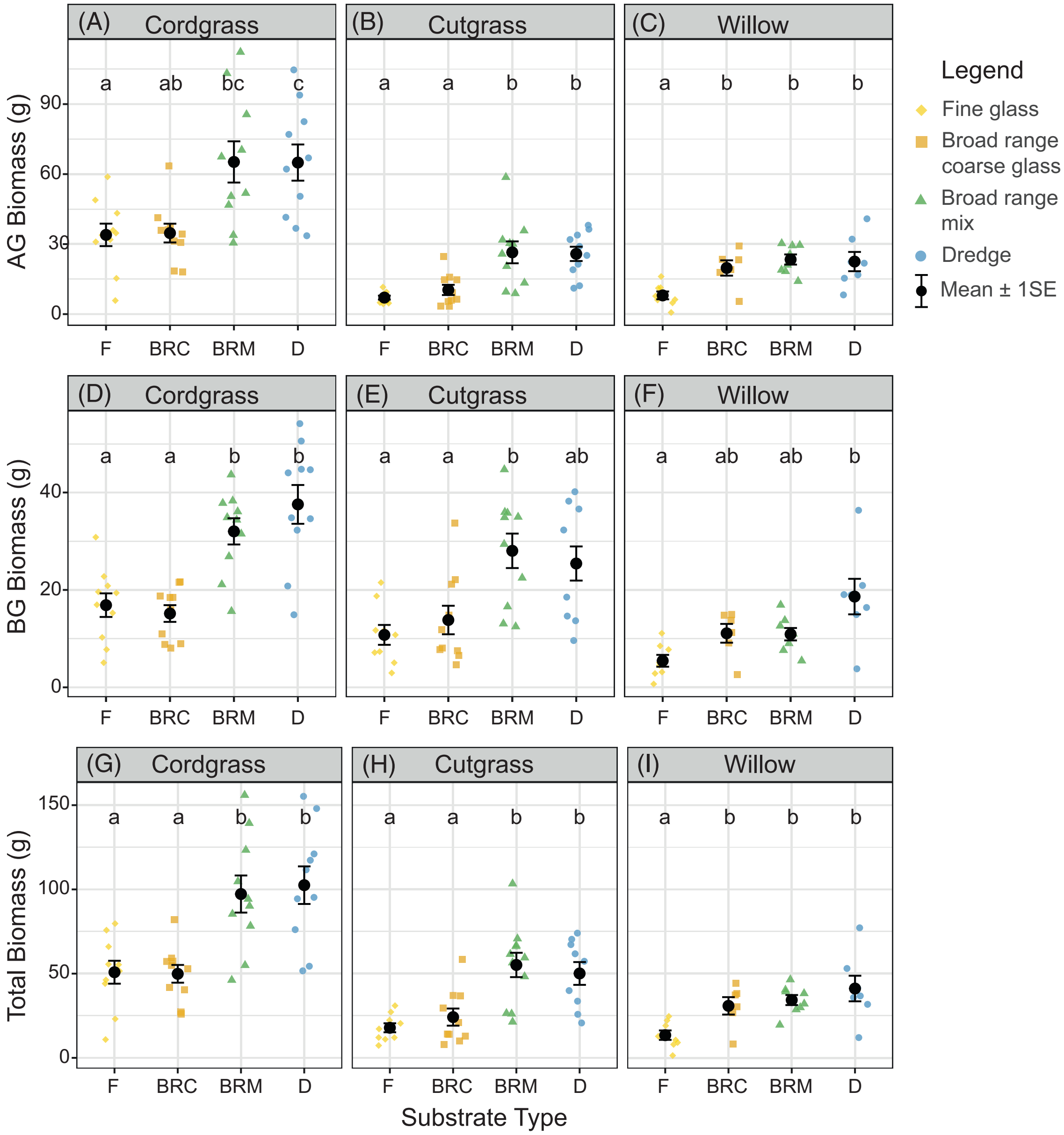

Figure 2. Plant biomass by substrate type and species in Experiment 1. (A–C) Aboveground (AG). (D–F) Belowground (BG). (G–I) Total (AG + BG). AG, BG, and total biomass responses were similar to one another. Plants grown in all-glass substrates (fine glass and broad range coarse glass) had lower growth than those grown in the broad range glass/dredge mix and those grown in dredge alone. In all cases, growth in the broad range glass/dredge mix was equivalent to growth in the dredge alone. While growth in the fine glass sand was typically lower than the growth in the broad range mix or dredge, growth in the broad range coarse glass sand was in several cases comparable to the growth in the broad range mix or dredge. The figure shows dry biomass mean ±1 SE across substrate types, by species. Letters above bars indicate differences as determined by a Tukey test, with $p = 0.05$ as the threshold of significance. Bars with shared Tukey letters have means that do not differ. BRC, broad range coarse glass; BRM, broad range glass/dredge mix; D, dredge; F, fine glass mix.

was a main effect of species ($F_{1,42} = 5.0$, $p = 0.031$), with Baldcypress biomass lower on average (Fig. 3C & 3D). Total biomass was not affected by species, substrate, or their interaction. These results are summarized in Table S3.

Substrate Physical Properties

Substrate types varied in physical properties as follows: particle density ($F_{5,24} = 26.8$, $p < 0.001$); compaction (not significant: $F_{5,24} = 2.2$, $p = 0.089$); dry, uncompressed bulk density ($F_{5,24} = 100.9$, $p < 0.001$); estimated saturated, compressed bulk density ($F_{5,24} = 32.9$, $p < 0.001$); dry, uncompressed porosity ($F_{5,24} = 6.8$, $p < 0.001$); and saturated, compressed porosity ($F_{5,24} = 26.8$, $p < 0.001$) (Table S4). Particles for all substrates were comparably dense (Fig. 4A). The only substrates whose compaction differed from each other were the broad range coarse glass and the mid-range mix (Fig. 4B). The dry, uncompressed bulk density was lowest in fine

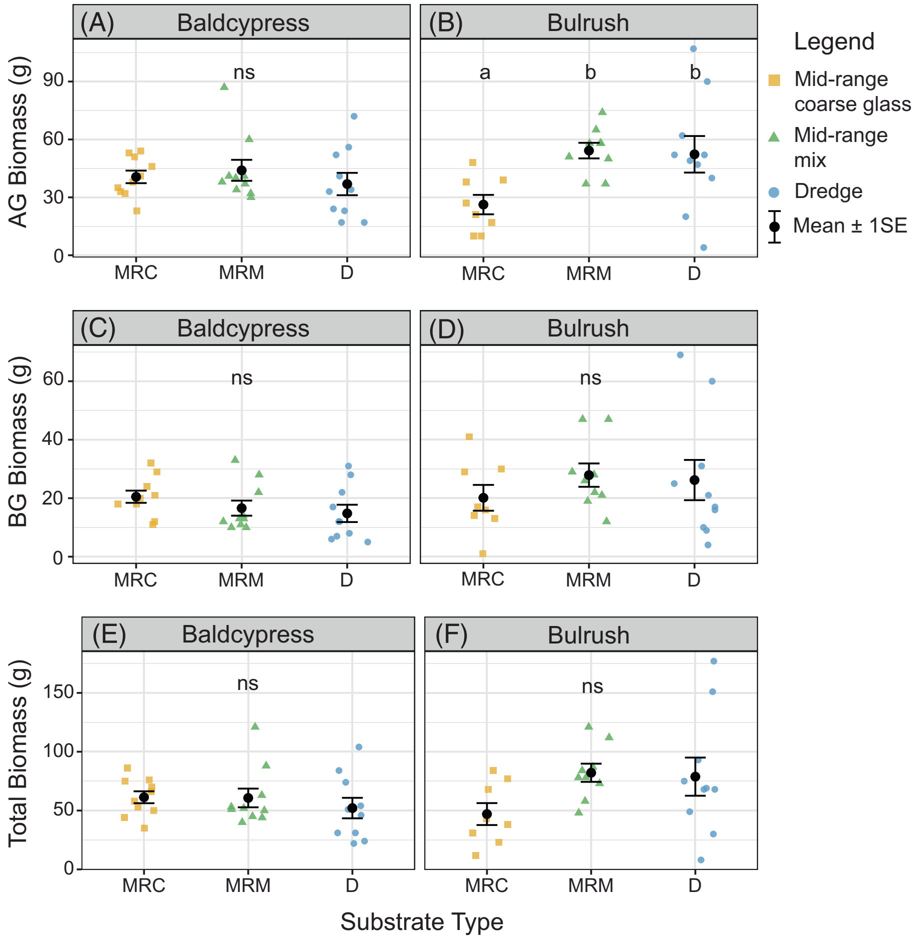

Figure 3. Plant biomass by substrate type and species in Experiment 2. (A and B) Aboveground (AG). (C and D) Belowground (BG). (E and F) Total (AG + BG). Baldcypress biomass was unaffected by soil type. Bulrush AG biomass was greater in the mid-range mix and dredge than in the mid-range coarse glass sand. The figure depicts dry biomass mean ±1 SE across substrate types, by species. Letters above bars indicate differences as determined by a Tukey's post-hoc test, with $p = 0.05$ as the threshold of significance. Bars with shared Tukey letters have means that do not differ. An "ns" denotes no significant difference between any treatments. D, dredge; MRC, mid-range coarse glass; MRM, mid-range glass/dredge mix.

glass and mid-range coarse glass, which were comparable to one another. The broad range coarse glass was denser than these, but less dense than the broad range mix, mid-range mix, and dredge, which were comparably dense to each other (Fig. 4C). The relative bulk densities of the saturated, compressed substrates were similar to those of the dry, uncompressed substrates, though the broad range coarse glass was comparable to both of the mixes and to the dredge (Fig. 4D). As can be expected of sandy substrates with low organic matter, all substrates had high bulk densities: average saturated bulk densities (±1 SE) ranged from 1.34 (± 0.02) g/cm^3 for fine glass to 1.69 (±0.03) g/cm^3 for broad range glass/dredge mix. The dry, uncompressed porosity was greatest in the fine glass, followed by the comparable mid-range coarse glass, which was also comparable to the broad range coarse glass and the dredge, but greater than both mixes, to which the broad range coarse glass and dredge were also comparable (Fig. 4E). The estimated porosity of the saturated, compressed substrate differed: the fine and broad range coarse glass blends had the lowest porosity, followed by the comparable broad range mix, the mid-range mix (which was comparable to the broad range mix), and the mid-range coarse glass and the dredge had the highest porosity (Fig. 4F).

Substrate and Leaf Chemistry (Experiment 2)

All substrates were below the medium range for potentially toxic metals (As, Cd, Ni, Pb) and were alkaline, ranging from dredge's average of 7.69 ± 0.15 SE to mid-range coarse glass's average of 9.82 ± 0.15 SE (Supplement S8). The PCAs and PERMANOVAS revealed that chemical profiles were significantly grouped by substrate type for both substrate samples ($F_{2,6} = 197.1$, $p = 0.003$; Table S5; Fig. 5A) and bulrush leaf samples ($F_{2,12} = 15.7$, $p = 0.001$; Table S6; Fig. 5B). For substrate samples (Fig. 5A), the first two principal components explained a cumulative 79.96% of the variation between samples. Mid-range coarse glass was associated with higher Zn levels and pH and lower levels of all other elements. Dredge and mid-range glass/dredge mix were associated with lower

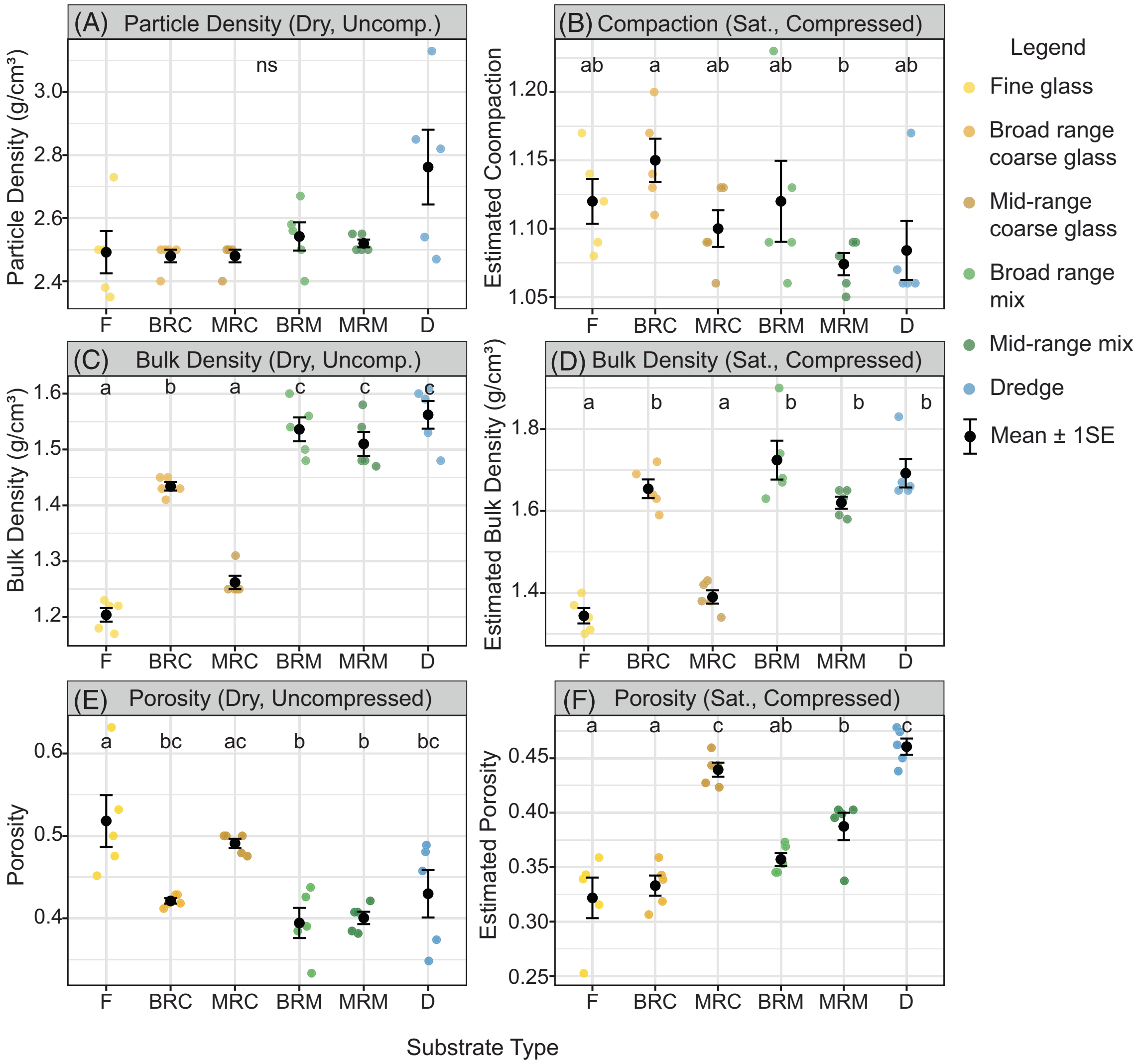

Figure 4. Physical properties of each substrate type: (A) Particle density of dry, uncompressed substrates; (B) Estimated compaction of saturated, compressed substrates; (C) Bulk density of dry, uncompressed substrates; (D) Estimated bulk density of saturated, compressed substrates; (E) Porosity of dry, uncompressed substrates; (F) Estimated porosity of saturated, compressed substrates. For each physical property, the figure depicts mean ± 1 SE across substrate types. Differences between treatments were determined by a Tukey's post-hoc test, with $p = 0.05$ as the threshold of significance. These differences are indicated by different letters over the data; bars that share a letter have means that do not differ. Saturated, compressed bulk density was estimated based on the average uncompressed dry density of each substrate type, the volume of saturated uncompressed substrate, and the volume of saturated compressed substrate. This estimated bulk density was used to estimate saturated compressed compaction and porosity. BRC, broad range coarse glass; BRM, broad range glass/dredge mix; D, dredge; F, fine glass mix; MRC, mid-range coarse glass; MRM, mid-range glass/dredge mix.

Zn levels and pH, and higher levels of most nutrients including Mg, P, and Cu, as well as toxins including Pb and As. Dredge was differentiated from mid-range glass/dredge mix by having higher levels of Cd, Ni, Ca, and As, while mid-range glass/dredge mix had higher levels of all other elements. For bulrush samples (Fig. 5B), the first two principal components explained a cumulative 53.54% of the variation between samples. Similarly to the soil chemistry, bulrush grown in mid-range coarse glass sand was associated with greater Zn and lower levels of Mg, S, Ni, Ca, and Mn. Bulrush grown in dredge was associated with greater levels of these elements, and those grown in the mid-range glass/dredge mix were associated with intermediate levels. Bulrush grown in the mid-range glass/dredge mix was generally neutral or positively associated with N, whereas those grown in mid-range coarse glass sand were negatively associated with N, and those grown in dredge varied greatly in N. Bulrush varied in C, Cu, Fe, and K regardless of substrate type.

Discussion

Biomass

Our study shows that coastal wetland plants can successfully grow in recycled glass sand, suggesting it is a viable and vital

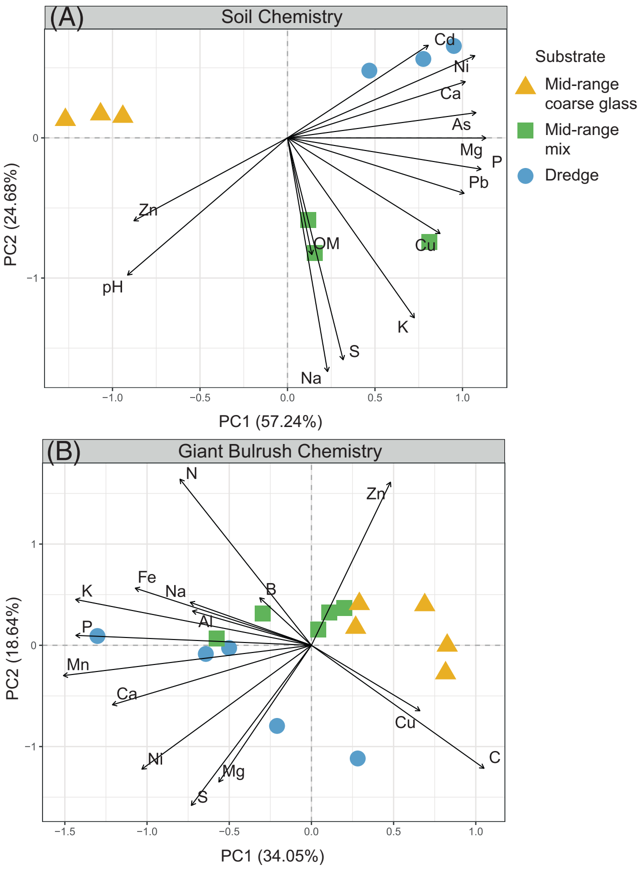

Figure 5. Principal component analysis of the Experiment 2 substrate (A) and Giant bulrush (B) chemistry. (A) The chemical profiles of substrate samples differ by substrate type. (B) Bulrush chemical profiles also differ from one another based on the substrate type in which they were grown. Bulrush from mid-range glass/dredge mix is intermediate between those from dredge and mid-range coarse glass.

supplement for coastal land building and wetland remediation in the Gulf Coast and beyond. Plants grew equally well in dredge and glass/dredge mixes. This is consistent with Levine et al. (2025, this special collection)'s findings that two wetland species (*Juncus roemerianus* and *Sporobolus pumilus*) had comparable belowground biomass and rooting depth when grown in dredged sand compared to equal mixes of dredged sand and glass sand.

The proportion of glass used in a restoration project could impact which plants succeed. The variable response to glass/dredge mixtures in this study indicates that plant growth is not linear relative to the proportion of glass to dredge. Additionally, depending on species, there may be different optimal mixtures of glass to dredge. Indeed, both species in Levine et al. (2025) were herbaceous and differed in the proportion of glass where they grew best. They suggested that adaptation to high marsh versus low marsh could play a role. More studies should examine how the proportions of glass versus dredge affect coastal plant growth, comparing either woody to herbaceous species or high to low marsh.

Our prediction that the plant growth would be greater in dredge than in glass sand was supported by the data for herbaceous plants, but not for woody plants. The prediction that plant growth would be greater in fine glass than in broad-range coarse glass was not supported by the data. Notably, both woody species (Black willow and Baldcypress) grew just as well in the coarse sands as they did in the mixes and dredge, whereas the herbaceous species (Smooth cordgrass, Giant cutgrass, and Giant bulrush) tended to have lower growth in the glass sands, but comparable growth in the mixes and the dredge. The predictions for glass sand versus dredged sand were based on the hypothesis that finer grain sizes would benefit the plants the most; because the results differed from the predictions, plant growth was likely impacted by other physical or chemical properties of the substrates.

Substrate Physical Properties

Though substrates within each experiment did not differ from one another in particle density or compaction, they did differ in both bulk density and porosity. The bulk density of natural marshes in the region has been measured as 0.44–1.09 g/cm^3 (Murphy & Biber 2023). Constructed dredge wetlands have a much greater bulk density than their natural counterparts, although the relative grain sizes are variable (Edwards & Proffitt 2003; Murphy & Biber 2023). At least part of this can be explained by their much lower organic matter (Edwards & Proffitt 2003; Murphy & Biber 2023), as organic matter is less dense than mineral soil. Likewise, the average saturated, compressed bulk densities for all substrates exceeded this range, and yet the substrate types that supported more growth (dredge and the glass/dredge mixes) typically had greater bulk densities than those that supported less growth (fine and coarse glass sands). If bulk density were the primary inhibition to plant growth, we would expect the least growth to have occurred in the dredge and glass/dredge mixes, and the most to have occurred in the glass. Substrate penetrability may still have been greater in the glass sand, despite the relatively low bulk density; other physical properties of the substrate not tested here, such as the grain shape and organization of pore space, can impact penetrability (Lipiec et al. 2016). In fact, while we did not include root shape in this study, we did observe some differences in the shape of roots grown in each substrate type that could be consistent with greater impedance within the glass: roots grown in glass substrates appeared generally thicker and less straight than those grown in dredge (EM, personal observation). Consistent with this observation, Fronabarger et al. (n.d. in revision, this special collection) found that Black mangrove grown in glass sand had shorter, thicker roots than those grown in dredged sand. Thicker roots can help plants penetrate hard soil (Materechera et al. 1992), which would explain the observed possible difference in diameter and why the tree species tended to grow better in the coarse glass than the herbaceous species. Future research could study the causes and implications of altered root shape in glass sand.

For the first experiment, dredge had greater porosity than the other substrates. For the second experiment, dredge and the mid-range coarse sand had similar porosities, whereas the mid-range mix had a lower porosity. These differences can help explain the biomass data when we consider what they might mean for a related structural variable, the macropore volume. Macropores can provide channels for root growth, but excessive pore space can reduce the substrate-root interface. Controlling for bulk density, Giuliani et al. (2024) found a species-specific impact of macropore structure on root growth, with thicker-rooted species growing better in soil structured with macropores and thinner-rooted species growing better in soil without. Due to the prevalence of fine grains within all Experiment 1 treatments and the brief timescale of each experiment, it seems likely that these substrates would have had a low macropore volume: finer grains could have filled the gaps between larger grains, reducing the pore size. This supports the idea that lower herbaceous growth within the fine and broad range coarse glass could have been driven by a lower penetrability of the glass-only treatments. In contrast, the absence of finer grains in Experiment 2's mid-range coarse glass, along with its greater porosity, suggests that the pore spaces in this substrate would have been generally larger. The mid-range mix of glass and sand had a lower porosity than the other Experiment 2 substrates, suggesting greater packing overall. Greater macropores in the mid-range coarse glass would explain why the thick-rooted Baldcypress' AG biomass was not impacted by substrate type, whereas the fine-rooted Giant bulrush had lower growth in the mid-range coarse glass. The Baldcypress may have had sufficient contact with this substrate, whereas the bulrush may not have. While the substrate origins and physical properties such as pore space may have impacted mutualistic or antagonistic plant-microbe interactions, a future study on this topic will have to address this effect.

Substrate and Leaf Chemistry (Experiment 2)

We predicted that key nutrients N, P, and K would be greatest in the plants from dredge, moderate in the plants from the broad range glass/dredge mix, and least in the plants from the broad range coarse glass sand. These predictions were partially supported: bulrush samples from the dredge were more associated with P and K than bulrush samples from the broad range coarse glass. However, N was most consistently positively associated with bulrush samples from the mid-range glass/dredge mix, not with bulrush from the dredge as predicted. Two possible explanations for these results include (1) soil chemistry related to soil structure and (2) the starting nutrient profiles of each substrate.

Regarding soil chemistry, although the grain size distribution of the mid-range glass/dredge mix was skewed larger than that of the dredge, this does not seem to have inhibited plant uptake of N. Because the bulrush grown in coarse glass sand were negatively associated with N, the lack of fine grains in this substrate may be interfering with nutrient retention (Zedler 1998). It may be advantageous to amend coarse glass mixtures with fine grains or use them at sites where silts will more readily accumulate.

Regarding the starting nutrient profiles, each substrate type had a distinct chemical (nutrients, metals, and pH) profile, and plants grown within those substrate types also had distinct chemical (nutrients and metals) profiles that shared many characteristics with the corresponding substrate chemical profile (such as increased Zn for glass or increased Ca, K, Mg, Ni, and P for mix and dredge). These similarities between the substrate and leaf contents provide a potential explanation for the differences in plant growth between substrate types: plant species may respond to differences in nutrient availability—or heavy metal presence—between the substrate types, despite the light fertilization of both experiments. If the relatively lower biomass of some species in glass sand can be attributed to the lower nutrient content of the sand, then these differences should be minimized in nutrient-rich waters, or over time as organic matter accumulates within the substrates—provided that plants are initially able to establish and stabilize glass sand. A further implication of these findings is that in areas where dredged sand may be contaminated, for example, with Cd, adding glass sand may reduce the resulting Cd levels in plants.

Other factors that we did not test can influence the correlation between soil and leaf chemistry or even between nutrient presence and uptake. As Hartemink and Barrow (2023) discuss, many factors, such as pH, redox conditions, and plant and microbial activity, contribute to nutrient and metal uptake in plants, even in conflicting ways: for example, in highly acidic soils, both sorption and desorption of P increase, as does plant uptake. Thus, while wetland plant leaf contents are influenced by soil contents, the strength and direction of these influences may be dependent on the environmental conditions of a restored coastal wetland and biotic interactions. Future research should study how chemical differences between glass, dredge, and natural wetlands persist over time in different environments.

While dredge and glass sand differ in their physical and chemical properties as shown in this study, dredge itself differs from naturally deposited wetland soil, and thus represents the status quo material—not the gold standard—for wetland construction in the US Gulf States. Dredge-constructed coastal wetlands chemically differ from natural wetlands. They have been found to have lower nitrogen (Fearnley 2008) and differing nutrients and metals (Lee et al. 2024). Possible soil amendments include adding organics (Fearnley 2008) or fine-particle materials (Callaway 2001 as cited in Zedler & Kercher 2005) to improve soil quality. Amendments such as these could further minimize differences between glass and dredge.

Further Considerations

Constructed coastal wetlands can take decades to approach the function of natural wetlands (Boorman & Garbutt 2012). Determining how successful glass sand wetlands can be will require field deployment and longer-term monitoring, which should be paired with an Adaptive Restoration (Zedler 2017) approach, as described below. The greenhouse experiments discussed in this paper provided a relatively short-term, controlled system in which to study the effect of glass sand versus dredged sand on plant biomass: plants only experienced one growing season; lighting, nutrient input, and water were all manipulated; water was fresh; pots contained soil, preventing erosion; and the plants were removed from the numerous flora, fauna, and microbiota that would be expected of a more natural environment. In contrast, field deployments provide the opportunity to study how constructed environments mature over time in a more natural setting. This includes resistance to erosion, organic matter accumulation, and species establishment and competition. Properly monitored field deployments can also highlight regionally specific ecological consequences. For example, Zedler (1998) reported how the texture of dredged sand used in one project had cascading effects on the site's soil nutrients, vegetation growth, habitat quality, and invasibility. Another limitation of this study is that it fully mixed the glass sand and dredge, though other constructions such as glass as a base fill topped with dredge, or alternate layering are possible, and perhaps more likely in a field setting where mixing glass and dredge might entail an extra step, or at flooded sites where natural sorting may occur as sediments settle. Further, the relative strength of substrate's effect on biomass compared to that of other variables in a restoration such as elevation and planting strategy has not been explored. The many possible ways to incorporate glass sand in coastal restorations make it an excellent candidate for Adaptive Restoration (Zedler 2017), where multiple different techniques are tested in tandem, and the most successful ones are carried through.

The landscape of restoration projects is diverse: they differ in objectives, urgency, scale, and resources. Where a project's objective is complex, such as maximizing the ecosystem services of a restored wetland, its use of glass sand would be best informed by the use of Adaptive Restoration as discussed above. Where a project's objective is simple, and the urgency is high, such as creating protective berms to mitigate storm damage, access to glass sand could be the difference between having a wetland or losing it entirely. Transporting substrate, whether dredged sand or glass sand, involves cost and logistical challenges. The distance substrate must be transported is the distance between the desired restoration site and the available substrate. Thus, for glass sand to be broadly accessible, there will need to be multiple sources of it. Glass sand has already been put to use in some locations in Louisiana, including creating a protective berm at Big Branch Marsh National Wildlife Refuge, St. Tammany Parish (ReCoast 2023), and building a small, experimental island in a degraded swamp (ReCoast 2024). Projects like these could serve as models for future restorations, particularly for regions where rapid, widespread land loss is combined with limited substrate supply.

The first criterion for a successful coastal wetland restoration must be the establishment of appropriate vegetation (Boorman & Garbutt 2012). By demonstrating that recycled glass sand supports wetland plant growth in a controlled greenhouse environment, this study establishes glass sand's potential for successful coastal wetland restoration and justifies further research into its applications for coastal protection, including experimenting with different implementation strategies. Additionally, by complementing biomass data with soil physical and chemical properties and leaf chemistry, this study provides direction for future research.

Acknowledgments

This work was supported by the National Science Foundation Convergence Accelerator Program through Award Numbers 2230769 and 2137730. The project was conducted as part of the ReCoast team, led by Dr. Julie Albert at Tulane. We are grateful to the current and former members of the Van Bael lab and to our many other volunteers for their help. Thanks as well to those who donated materials for this study, as noted in the text, to Tulane's Hebert Center (Belle Chasse, LA, U.S.A.) for long term storage of samples, and to Franta Majs at LSU's STPAL for advice on sampling for nutrient testing.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

LITERATURE CITED

Ahmad S, Tamayo S, Molina D, Borne N, Michaeloff L, Trautmann F, Vanegas J, Albert J (n.d.) Physical–chemical characterization of recycled glass sand for environmental restoration. Restoration Ecology (in review, this special collection).

Barrow NJ, Whelan BR (1998) Comparing the effects of pH on the sorption of metals by soil and by goethite, and on uptake by plants. European Journal of Soil Science 49:683–692. https://doi.org/10.1046/j.1365-2389.1998.4940683.x

Bilkovic DM, Mitchell M, Mason P, Duhring K (2016) The role of living shorelines as estuarine habitat conservation strategies. Coastal Management 44:161–174. https://doi.org/10.1080/08920753.2016.1160201

Boesch DF, Josselyn MN, Mehta AJ, Morris JT, Nuttle WK, Simenstad CA, Swift DJP (1994) Scientific assessment of coastal wetland loss, restoration and management in Louisiana. Journal of Coastal Research, Special Issue No. 20:i–v, 1–103. https://www.jstor.org/stable/25735693

Boorman LA, Garbutt A (2012) Restoration strategies for intertidal salt marshes. Pages 189–215. In: Wolanski E, McLusky D (eds) Treatise on estuarine and coastal science. Academic Press, Waltham, MA.

Buczkowski B, Reid JA, Schweitzer PN, Cross VA, Jenkins CJ (2020) usSEABED: Offshore surficial-sediment database for samples collected within the United States Exclusive Economic Zone. U.S. Geological Survey. [csv]. https://doi.org/10.5066/P9H3LGWM (accessed 21 June 2024)

Connelly J, Jensen W, Harmon P (2008) Proctor compaction testing. Nebraska Department of Transportation Research Reports. 31.

Couvillion B, Barras J, Steyer G, Sleavin W, Fischer M, Beck H, Trahan N, Griffin B, Heckman D (2011) Land area change in coastal Louisiana from 1932 to 2010 (Scientific Investigations Map) [Pamphlet]. https://pubs.usgs.gov/sim/3164/downloads/SIM3164_Pamphlet.pdf (accessed 5 February 2025)

CPRA (Coastal Protection and Restoration Authority of Louisiana) (2023) Louisiana's comprehensive master plan for a sustainable coast. https://coastal.la.gov/our-plan/2023-coastal-master-plan/ (accessed 5 February 2025)

Day JW, Britsch LD, Hawes SR, Shaffer GP, Reed DJ, Cahoon D (2000) Pattern and process of land loss in the Mississippi Delta: a spatial and temporal analysis of wetland habitat change. Estuaries 23:425–438. https://doi.org/10.2307/1353136

Dokka RK (2011) The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. Journal of Geophysical Research: Solid Earth 116:B06403. https://doi.org/10.1029/2010JB008008

Edwards KR, Proffitt CE (2003) Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. Wetlands 23:344–356. https://doi.org/10.1672/10-20

Fearnley S (2008) The soil physical and chemical properties of restored and natural back-barrier salt marsh on isles Dernieres, Louisiana. Journal of Coastal Research 24:84–94. https://doi.org/10.2112/05-0620.1

Fox J, Weisberg S, Price B, Adler D, Bates D, Baud-Bovy G, et al. (2024) car: Companion to applied regression.

Fronabarger K, Deogracias A, Lange K, MacDougal E, Markel B, Van Bael S, Farrer E (n.d.) Recycled glass sand as an artificial substrate for coastal restoration: a test with black mangrove (*Avicennia germinans*). Restoration Ecology (in revision, this special collection).

Giuliani LM, Hallett PD, Loades KW (2024) Effects of soil structure complexity to root growth of plants with contrasting root architecture. Soil and Tillage Research 238:106023. https://doi.org/10.1016/j.still.2024.106023

Hartemink AE, Barrow NJ (2023) Soil pH – nutrient relationships: the diagram. Plant and Soil 486:209–215. https://doi.org/10.1007/s11104-022-05861-z

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biometrical Journal 50:346–363. https://doi.org/10.1002/bimj.200810425

Jackson CR, Thompson JA, Kolka RK (2019) 2. Wetland soils, hydrology, and geomorphology. Pages 23–60. In: Batzer DP, Sharitz RR (eds) Ecology of freshwater and estuarine wetlands. University of California Press, Berkeley

Kulp M, Penland S, Williams SJ, Jenkins C, Flocks J, Kindinger J (2005) Geologic framework, evolution, and sediment resources for restoration of the Louisiana coastal zone. Journal of Coastal Research 44:56–71. http://www.jstor.org/stable/25737049

Lee H, Diaz R, Cronin JT (2024) Dieback and dredge soils of *Phragmites australis* in the Mississippi River Delta negatively impact plant biomass. Scientific Reports 14:1935. https://doi.org/10.1038/s41598-024-52488-4

Levine AJ, Sparks E, Biber P, Woodrey MS (2025) Efficacy of recycled glass sand as a soil substrate for salt marsh restoration. Restoration Ecology. https://doi.org/10.1111/rec.14369

Li CH, Ma BL, Zhang TQ (2002) Soil bulk density effects on soil microbial populations and enzyme activities during the growth of maize (*Zea mays L.*) planted in large pots under field exposure. Canadian Journal of Soil Science 82:147–154. https://doi.org/10.4141/S01-026

Lipiec J, Siczek A, Sochan A, Bieganowski A (2016) Effect of sand grain shape on root and shoot growth of wheat seedlings. Geoderma 265:1–5. https://doi.org/10.1016/j.geoderma.2015.10.022

Makowski C, Finkl CW, Rusenko K (2011) Using recycled glass cullet for coastal protection: a review of geotechnical, biological, & abiotic analyses. Journal of Coastal Research 64:362–1366. https://www.jstor.org/stable/26482398

Makowski C, Finkl CW, Rusenko K (2013) Suitability of recycled glass cullet as artificial dune fill along coastal environments. Journal of Coastal Research 29:772–782. https://doi.org/10.2112/12A-00012.1

Makowski C, Rusenko K (2007) Recycled glass cullet as an alternative beach fill material: results of biological and chemical analyses. Journal of Coastal Research 23:545–552. https://doi.org/10.2112/06-0715.1

Materechera SA, Alston AM, Kirby JM, Dexter AR (1992) Influence of root diameter on the penetration of seminal roots into a compacted subsoil. Plant and Soil 144:297–303. https://doi.org/10.1007/BF00012888

Morgan JB, Connolly EL (2013) Plant–soil interactions: nutrient uptake | learn science at scitable. Nature Education Knowledge 4:2

Murphy NR, Biber P (2023) Comparison of vegetation community diversity, biomass, and sediment properties among constructed and reference salt marshes at deer Island, Mississippi, U.S.A. Qeios. https://doi.org/10.32388/VZ74UK

Murray NJ, Worthington TA, Bunting P, Duce S, Hagger V, Lovelock CE, et al. (2022) High-resolution mapping of losses and gains of Earth's tidal wetlands. Science 376:744–749. https://doi.org/10.1126/science.abm9583

Neina D (2019) The role of soil pH in plant nutrition and soil remediation. Applied and Environmental Soil Science 2019:1–9. https://doi.org/10.1155/2019/5794869

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, et al. (2024) vegan: community ecology package.

Okwan P, Zhen Y, Feng H, Yoo S, Kambhampati MS, Walker A, et al (2020) Statistical analysis of nutrient loads from the Mississippi-Atchafalaya River Basin (MARB) to the Gulf of Mexico. Environments 7:8. https://doi.org/10.3390/environments7010008

Passioura JB (2002) Soil conditions and plant growth. Plant, Cell & Environment 25:311–318. https://doi.org/10.1046/j.0016-8025.2001.00802.x

Pinheiro JC, Bates DM (2000) Mixed-effects models in S and S-PLUS. Springer, New York

R Core Team (2023) R: a language and environment for statistical computing (4.3.0) [computer software]. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org

ReCoast (2023) Berm | Big Branch. https://recycleforthecoast.org/berm-big-branch (accessed 6 February 2025)

ReCoast (2024) Islands | Bayou Bienvenue. https://recycleforthecoast.org/islands-bayou-bienvenue (accessed 6 February 2025)

Shaffer GP, Wood WB, Hoeppner SS, Perkins TE, Zoller J, Kandalepas D (2009) Degradation of baldcypress—water tupelo swamp to marsh and open water in southeastern Louisiana, U.S.A.: An irreversible trajectory? Journal of Coastal Research 2009:152–165. https://doi.org/10.2112/SI54-006.1

Tahir S, Marschner P (2017) Clay addition to sandy soil—influence of clay type and size on nutrient availability in sandy soils amended with residues differing in C/N ratio. Pedosphere 27:293–305. https://doi.org/10.1016/S1002-0160(17)60317-5

Turner RE (1997) Wetland loss in the northern Gulf of Mexico: multiple working hypotheses. Estuaries 20:1–13. https://doi.org/10.2307/1352716

Wang Q, Wen Y, Zhao B, Hong H, Liao R, Li J, Liu J, Lu H, Yan C (2021) Coastal soil texture controls soil organic carbon distribution and storage of mangroves in China. Catena 207:105709. https://doi.org/10.1016/j.catena.2021.105709

Wentworth CK (1922) A scale of grade and class terms for clastic sediments. The Journal of Geology 30:377–392. https://doi.org/10.1086/622910

White PJ, Brown PH (2010) Plant nutrition for sustainable development and global health. Annals of Botany 105:1073–1080. https://doi.org/10.1093/aob/mcq085

Zedler JB (1998) Replacing endangered species habitat: the acid test of wetland ecology. Pages 364–379. In: Conservation biology for the coming age. Chapman & Hall, New York

Zedler JB (2017) What's new in adaptive management and restoration of coasts and estuaries? Estuaries and Coasts 40:1–21. https://doi.org/10.1007/s12237-016-0162-5

Zedler JB, Kercher S (2005) Wetland resources: status, trends, ecosystem services, and restorability. Annual Review of Environment and Resources 30:39–74. https://doi.org/10.1146/annurev.energy.30.050504.144248

Supporting Information

The following information may be found in the online version of this article:

Supplement S1: Bucket setup.
Table S1: Greenhouse setup for Experiments 1 and 2.
Supplement S2: Experiment 1 initial plant size measurements.
Supplement S3: Experiment 2 initial plant size measurements.
Figure S1: Experiment 1 initial plant sizes across substrates.
Figure S2: Experiment 2 initial plant sizes across substrates.
Supplement S4: Experiment 1 species and planting information.
Supplement S5: Experiment 1 watering and lighting.
Supplement S6: Experiment 2 species and planting information.

Supplement S7: Experiment 2 watering and lighting.
Table S2: Experiment 1 biomass ANOVA results.
Table S3: Experiment 2 biomass ANOVA results.
Table S4: Substrate physical properties ANOVA results.
Supplement S8: Soil nutrient and metal concentrations.
Table S5: PERMANOVA of Experiment 2 substrate chemistry.
Table S6: PERMANOVA of Giant bulrush leaf chemistry.

Guest Coordinating Editor: Lily Pfeifer

Received: 4 October, 2024; First decision: 13 November, 2024; Revised: 12 February, 2025; Accepted: 13 February, 2025