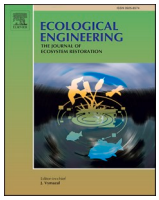
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Using dredged sediments to support wetland plant development in a constructed delta lake

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ABSTRACT

Restoration efforts take place at large scales to improve the ecological value of degraded, modified river deltas. To anticipate on the implications of using dredged, estuarine sediment to restore wetlands in river deltas, we studied the development of *Typha latifolia* (cattail) and *Phragmites australis* (common reed) on two designated dredged sediments, virgin Holocene clay (clay) and eroded clay (mud), under different water levels (inundated, saturated, and moist) in a mesocosm experiment. The mud sediment contained about two times higher Fe, S, and P content and four times higher N-total content compared to clay sediment. The organic content was comparable for both sediments. Sediment type influenced germination and shoot growth of *T. latifolia*, which were both higher on clay compared to mud, but did not influence germination and initial growth of *P. australis*. Water level treatment effects on plant response were limited to inundation conditions only; this condition strongly reduced *P. australis* seedling and shoot development. Both species developed significantly more above- and belowground biomass when growing in mud compared to clay, however, their nutrient content was comparable on both sediment types. Overall, *T. latifolia* development was more strongly influenced by sediment composition compared to *P. australis*, but the latter species is more vulnerable to higher water levels during early stages of development. We conclude that both dredged sediment types are suitable as sediment for developing macrophyte vegetation.

1. Introduction

River deltas in densely populated areas are often heavily modified by hydraulic engineering (Coleman et al., 2008; Maselli and Trincardi, 2013; Vörösmarty et al., 2009) and have lost their natural, dynamic processes. As a result, accumulating silt in rivers and estuaries is dredged regularly (Brils et al., 2014). Dredged sediment that might contain effluent-derived heavy metals or toxic elements is often stored in allocated sites, but unpolluted dredged sediments could be utilized as construction material in ecological engineering. As suggested in Brils et al. (2014), there are examples of using dredged sediments to restore eroded islands in the Chesapeake Bay, Maryland (Dalal et al., 1999; Erwin et al., 2007), to create coastal wetlands (Wallasea Project, United Kingdom; Cross, 2017, Dixon et al., 2008), to create and restore dredged material salt marshes the Northern Gulf of Mexico, Texas (Armitage, 2021; Shafer and Streever, 2000; Stagg and Mendelssohn, 2011) and more recently to construct the Marker Wadden, an archipelago of wetlands in Lake Markermeer, the Netherlands.

Ecological engineering focusses on designing novel ecosystems in such a way that natural processes can be used to promote self-design, enhance and accelerate ecosystem development, or replace conventional engineering structures (Mitsch, 1998). Successful eco-engineering using dredged sediments therefore requires understanding on how ecological, geomechanical and hydrological processes interact to define an optimal design to stimulate wetland development (Temmerman et al., 2013). One of the key components in wetland development is emergent vegetation germination and development. Emergent plants can develop quickly during the first years after the construction of wetlands and contribute to the formation and stabilization of soils and to the accumulation of organic matter (Mitsch et al., 2012). In cases where dredged sediment is used, plant roots can stabilize the unsolidified, soft sediment during the early phase of soil formation (Saaltink et al., 2018),

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and generate habitat and food sources for associated fauna. This would make sowing of plants an effective tool to accelerate and catalyse soil formation and consolidation to obtain a stable, nutrient providing soil as a robust base for sustainable ecological development.

In this study we focussed on the use of dredged sediments to construct wetlands in the Lake Markermeer wetland ecological engineering project Marker Wadden. Lake Markermeer is located in the former Zuiderzee estuary, and was disconnected from the sea by embankments in the first half of the 20th century. Hydrological isolation in combination with erosion of the marine bottom sediment has led to excessive mud accumulation in the Lake (Kelderman et al., 2012; Vijverberg et al., 2011; Genseberger et al., 2016). We tested whether plants successfully germinate and develop on these sediments, and initiate primary ecological development, and in this way could contribute to stabilizing and consolidating the soil if this material would be used to construct wetlands. The marine origin and physical-chemical characteristics of the dredged sediments might have implications for germination and early plant development. Soil formation in dredged sediments may affect nutrient availability for the developing plants, as a result of oxidation and consolidation processes (Van den Berg et al., 2014; Vonk et al., 2017). Germination of wetland plants furthermore depends on water levels, with lowering water tables stimulating seed germination and plant growth (Van Leeuwen et al., 2014). Depending on their treats, plant species will respond differently to these processes.

In a mesocosm experiment plant germination, growth, and maturation of two wetland pioneer plant species, *T. latifolia* (cattail) and *P. australis* (common reed), were determined on virgin Holocene clay (clay) and eroded clay (mud) under inundated, saturated and moist sediment conditions. We hypothesize that sediment characteristics, plant species, and water levels may influence germination and early plant development on dredged sediments.

2. Material and methods

2.1. Study site

Lake Markermeer is part of an estuarine area, which has been modified to freshwater basins on marine deposits. It has a surface area of about 68,000 ha and an average depth of 3.6 m (Van Duin, 1992). Due to its groyne stone diked shores, the Lake lacks gradual land-water transitions, shallow areas, and natural shores. Clay and sandy clay form 75% of the bottom surface. Peat remnants occur locally. The composition of the upper layer of the water bottom (0–5 cm depth) ranges from more sandy components in the Northwest to lutum-containing deposits in the South (>35% lutum). The Lake's average calcium content is 15.6% (Winkels, 1995). Eco-engineering project Marker Wadden was designed to generate bird habitat by creating 10,000 ha of island wetlands and shallow zones. The project aims to decrease the burden of resuspending mud material in the Lake (Kelderman et al., 2012) by dredging eroded muddy lake-bed sediment and Holocene clay and use these sediments as construction material for the wetlands.

2.2. Sediment collection and characterization

Holocene clay sediment is the most common bottom sediment in Lake Markermeer (Kelderman et al., 2012; Winkels, 1995). This sediment is referred to as 'clay'. Wind induced currents eroded the Holocene clay surface into fluffy mud material that suspended easily in the water column, conglomerated with bacteria and algae (Brinkmann et al., 2019) and covered large surfaces of the Holocene clay. This sediment is referred to as 'mud'. The two sediment types have a very distinct geochemical composition, in terms of pyrite, iron-bound phosphorus and nutrients (Saaltink et al., 2016).

Holocene clay was collected from Lake Markermeer in February 2015 by mechanical dredging at one location (coordinates 52.5462°N; 5.3878°E) at 10–50 cm depth below the sediment surface. Median grain size (D50) was 60 μm. Mud was collected at several locations along the eastern shore of the Lake by mechanically dredging the upper 10 cm of the sediment. It consisted of very fine material (D50 = 16–32 μm), had a low sedimentation rate, and resuspended even at very low hydraulic loads. In total, 3 cubic metres of sediment was collected and transported in dark, closed containers to the research facility.

Subsamples of both sediment types were oven dried (70 °C, 48 h), homogenized, sieved on a 2 mm sieve, and ground to a particle size of <50 μm by colloid mill, before element analysis. Sediment Fe, Ca, and S content was analysed using induced coupled plasma atomic emission spectrometry (ICP-AES; Optima 8000, Perkin Elmer, USA) after performing a digestion with HNO_3/HCl on the sediment. Chloride content was analysed using flow injection analysis (FIA 5000, Sweden) after extracting the sediment with H_2O. Total P and total N were determined using segmented flow analysis (SFA-Nt/Pt, SKALAR, Breda, Netherlands) after performing a digestion on the sediment with H_2SO_4/H_2O_2/Se. Since there were indications that the phosphorous content in these Holocene sediments was bound to calcium or iron (Van den Berg et al., 2014), we also used Lyklema extraction (Hieltjes and Lyklema, 1980) to analyse the calcium-bound and iron-bound phosphorous content (P-Ca and P-Fe, respectively).

2.3. Mesocosm setup

In a mesocosm experiment sediment type, plant species, and water level were manipulated. The clay and mud sediments were collected from Lake Markermeer on February 24, 2015. Mesocosms (diameter 37.0 cm; height 42.5 cm; 30 l volume) were deployed with either a 30 cm layer of clay or mud on February 24–26. The sediment was left to settle inside the mesocosms for 17 days before 50 seeds of either *T. latifolia* or *P. australis* were added. The seeds were added to the sediments on March 14. This date is considered day one of the experiment. Unsown mesocosms functioned as control treatment. A total of 90 mesocosms were used to apply five replicates of each of the 18 treatments combinations; three plant treatments (i.e. two plant species and one unsown control), two sediment types, and three water level conditions (Fig. 1).

As plant seeds float on water, the water level treatments were not installed until the soil was stabilized and the germination process had initiated (April 4). During this initiation process, the sediments in the mesocosms were kept saturated. Due to the sediment settlement process, a < 1 cm water layer naturally occurred on the sediments' surface. Adding extra water to maintain saturated conditions was therefore not necessary. When germination had initiated, three different water levels were installed and maintained throughout the experiment using rainwater to mimic typical wetland conditions: inundated (+10 cm above sediment), saturated (~ + 1 cm), and moist conditions (unsaturated sediment). Mesocosm placement within the greenhouse was randomized. The mesocosm experiment was performed from February to July 2015, within the natural growing season, in a greenhouse in which conditions followed a natural daily regime for light and temperature conditions, with the greenhouse temperature control set to a minimum of 12 °C.

Environmental conditions in the experiment were measured regularly. Conductivity and pH were recorded weekly using a multi-meter (Hach Luminescent HQ10). Data loggers (HOBO pendant temperature/light data logger Part # UA-002-XX, Onset Computer Corporation, 2009) were installed to record the water temperature and light intensity at the benthic zones of inundated and saturated soil treatments every 15 min. Chlorophyll-a was analysed on filtered water samples (Whatman Glass Microfibre Filter GF/C, 1.2 μm pore size), which were collected on May 30. The analyses was performed with a PHYTHO-PAM fluorometer (PHYTO-ED, Walz GmbH Germany (Walz, 2003).

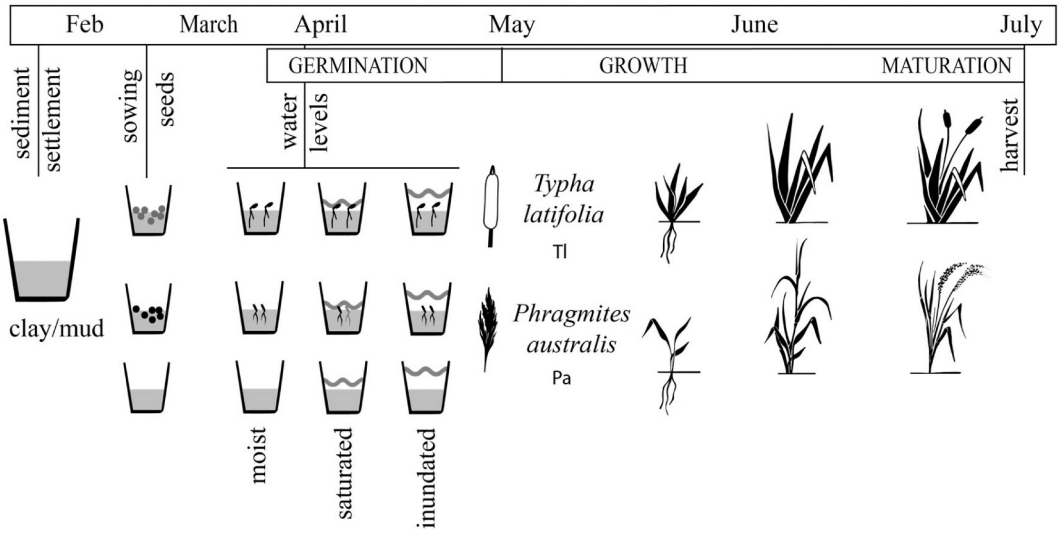


Fig. 1. Schematic overview of the experimental design and measurements, and the stages of plant development over time. Treatments consisted of two types of dredged sediment (clay and mud), three plant conditions (two plant types *Typha latifolia* and *Phragmites australis*, and an unsown, control condition and three water conditions (moist, saturated and inundated) with five replicates per combination of treatments, in total 90 mesocosms..

2.4. Germination, growth and analyses of plants

Three development phases were distinguished: 1) detection of seed germination, 2) assessment of plant growth, and 3) analyses of mature plants (Fig. 1). From week four after sowing until the end of the experiment the number of shoots in each mesocosm was counted weekly. During the growth phase, the length of the five tallest shoots were assessed weekly. In July, 120 days after sowing, all plants were harvested. Aboveground biomass was clipped, the number of shoots per mesocosm was counted, and the length of all shoots was measured. Belowground biomass was harvested and thoroughly rinsed. Dry weight of plant shoots, roots and rhizomes was determined after oven drying to a constant weight at 70 °C for 48 h.

For each treatment, 5 plants were randomly selected, mixed together, and ground to a particle size of <50 μm by colloid mill, and homogenized prior to chemical analysis. Total P and total N in the shoots were analysed using the same method as described for soil total P and total N analysis (SFA after digestion with H_2SO_4/H_2O_2/Se). Carbon content was analysed using a LECO carbon/nitrogen analyser (LECO CN 628 Dumas).

2.5. Statistical analysis

Effects of sediment type, water level, and plant species on vegetation development were analysed. Differences in germination and the number of shoots were analysed by means of logistic regression with the quasi-binomial distribution and a logit link, to test treatment effects and their interactions. Standardised residuals were normally distributed, also for the log-transformed parameters. Since *P. australis* development was minimal in the inundated mesocosms, this treatment was not considered for comparisons of plant growth (in terms of increasing length of the five tallest shoots in the mesocosm) and nutrient content. Consequently, the factorial structure of Plant x Water was broken, and the five remaining Plant x Water levels were combined into a single factor called PlantWater. ANOVAs were used to test for differences in log-length of the 5 tallest shoots. Differences in log biomass, and concentrations of N, P, and C in plant tissue were analysed using General Linear Models with Bonferroni post hoc testing ($p < 0.05$).

3. Results

3.1. Mesocosm and sediment characteristics

Surface water conductivity (1.54 ± 0.86 mS/cm on clay and 0.66 ± 0.42 mS/cm on mud; mean ± SD) and pH (range 8.5–9.0) were relatively constant during the experiment. Water temperatures in the mesocosms increased gradually during the spring/summer season, overall ranging from 14.6 °C to 26.8 °C during the growing season (mean 19.5 °C). Light intensity reached slightly higher values on clay than on mud (respectively $0.95*10^6 \pm 0.33*10^6$ lm/ft^2 and $0.62*10^6 \pm 0.27*10^6$ lm/ft^2 respectively under inundated conditions), but these reflected no light-limiting conditions. Chlorophyll-a concentrations in the water column was highly variable; algae development was temporary and disappeared within a few days. Under inundated conditions, averages of 154.1 ± 126.3 μg/l on clay and 305.8 ± 199.9 μg/l on mud were recorded. Both sediments had comparable percentages of organic material but differed in elemental composition. Mud sediment contained about a two times higher Fe, S and P-total content and a four times higher N-total content compared to clay sediment (Table 1).

Surface sediment structure and height were more variable in mesocosms with clay compared to those with mud substrate. This variation

Table 1
Sediment characteristics of the dredged clay and mud substrates used in the mesocosm experiment at the start of the experiment ($n = 4$). Iron-bound phosphorous (P-Fe) and calcium-bound phosphorous (P-Ca) contents were measured at the start (P-Ca start exp., P-Fe start exp.) and after the experiment had ended (P-Ca end exp., P-Fe end exp.).

Parameter	Unit	Clay		Mud	
Grain size D50	μm	60		16–32	
Organic content	%	8–12 (range)		8–12 (range)	
		Mean	sd	Mean	sd
Cl	g/kg	0.20	0.11	0.20	0.14
Ca	g/kg	41.49	3.84	58.03	2.56
Fe	g/kg	10.53	1.08	20.51	0.65
S	g/kg	3.74	0.46	8.45	0.58
Nt	g/kg	1.09	0.16	4.31	0.12
Pt	g/kg	0.30	0.02	0.50	0.04
P-Ca start exp.	g/kg	0.32	0.04	0.36	0.02
P-Ca endexp.	g/kg	0.27	0.02	0.30	0.04
P-Fe start exp.	g/kg	0.04	0.03	0.07	0.01
P-Fe end exp.	g/kg	0.02	0.01	0.07	0.02

was due to the loose structure of the latter, which was easily resuspended under experimental conditions; as a result, there was a comparatively more heterogeneous landscape on clay than on mud sediments at a microscale level (Fig. 2). A biofilm of algae developed on the mud sediment, but not on the clay sediment. These algae remained attached to the sediment particles.

3.2. Plant germination

Germination occurred from the last week of March to mid-May. As species development was limited to a few occasional individuals of *Zannichellia* spp. in the unsown control treatments, the dredged sediments were not seed sources for the plant species tested. There were highly significant differences in germination between the plant species ($p < 0.001$), with mean germination percentages of 29% for *P. australis* and 55% for *T. latifolia* (Fig. 3; Table 2). For *T. latifolia*, on average higher numbers of germinated seeds were observed on clay (68% ± 12%) than on mud (43% ± 9%), while substrate type did not affect germination of *P. australis*. This difference was reflected in a significant ($p = 0.025$) interaction for germination between plant species and sediment type (Table 2). There was no significant effect of the water level treatment, nor significant interactions with the water level treatment on the germination of the plants.

3.3. Plant growth

Water level treatments had profound effects on shoot numbers and lengths, with minimal shoot development in *P. australis* under inundated conditions (Fig. 4). Length increase of the five tallest shoots indicated that *T. latifolia* plants grew significantly larger on mud than on clay, irrespectively of water level treatment, while shoot length was comparable for *P. australis* on both sediment types under saturated as well as moist conditions. Excluding *P. australis* in the inundated treatments (PlantWater), the length of the five tallest shoots showed an interaction between sediment type and plant species ($p = 0.003$; Table 2). Further analysis of this interaction, employing contrasts between the predicted means, revealed that this interaction was solely caused by a large positive difference between mud and clay for *T. latifolia*. Diptera (fly) larvae occasionally developed in the soil and showed a profound effect on seedlings by stirring up the bottom and consuming the emergent plants. *Tipula lateralis* damaged the plants in one of the *P. australis* mesocosms, and occurred in one of the control treatment mesocosms. The mesocosms furthermore contained low numbers of *Oligochaeta* and *Chironomidae*, which had no damaging effect on plant development in the mesocosms.

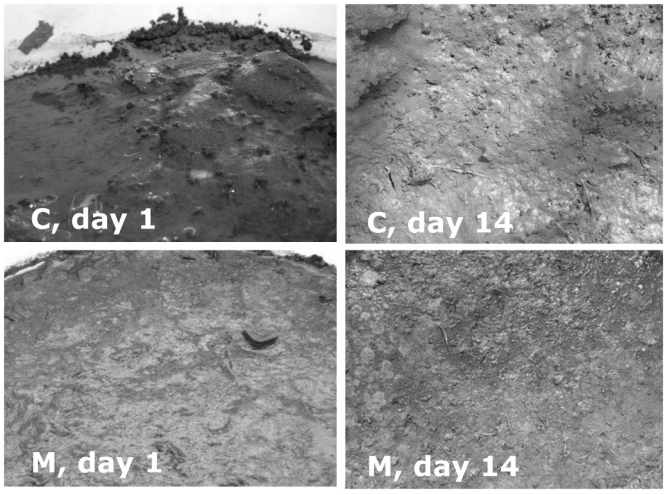


Fig. 2. Development of the upper surface of the clay (C, upper pictures) and mud (M, lower pictures) sediments in the mesocosms (initial condition on the left, condition after 2 weeks on the right).

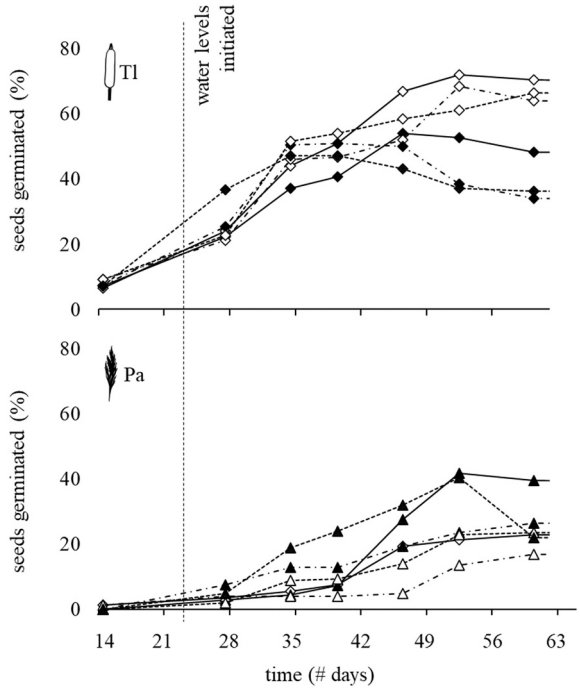


Fig. 3. Germination of *Typha latifolia* (top panel) and *Phragmites australis* (lower panel) under inundated (dotted lines), saturated (interrupted lines) and moist (solid lines) conditions on clay (open symbols) and mud (filled symbols) sediment in mesocosms ($n = 5$). Error bars are not presented in the figure in the interest of readability.

3.4. Mature plants

After 120 days, *P. australis* had developed significantly less shoots than *T. latifolia* (Fig. 5, Table 2). There was a highly significant ($p < 0.001$) sediment effect: average shoot dry weight on mud was a factor 2.8 larger than on clay.

Both plant species developed significantly more biomass aboveground ($p < 0.001$) and belowground ($p < 0.01$) growing on mud compared to growing on clay (Fig. 5). No effects of water level or plant species on biomass produced were observed (Table 2).

Plants developed more biomass and larger shoots when growing on mud compared to clay. Nutrient concentrations in harvested mature plants were not significantly different between water level treatments, sediment type or plant species (Table 3). Plant P content was high under all water level conditions for both *P. australis* (~1.8 mg P / g plant) and *T. latifolia* (2.5–3.0 mg P / g plant), indicating no nutrient limitations.

4. Discussion

4.1. Wetland plant development on dredged sediment types

Our experiment demonstrated that plants could successfully germinate, develop and mature on dredged sediments; however, different responses were observed for the three development phases of both plant species. Germination success was primarily determined by plant species. Overall, larger numbers of *T. latifolia* seeds germinated than *P. australis* seeds, regardless of the water level or sediment treatments. Germination of *T. latifolia* was more successful on clay than on mud, but substrate type did not influence the germination of *P. australis*. The most common factors that influence germination of wetland plants in general were comparable for the sediments used in the experiment (e.g. temperature,

Table 2
Summary of treatment effects on plant development in the mesocosms. Since *P. australis* did not develop under submerged conditions, only plant containing mesocoms were analysed by combining the plant x water levels into a single factor called PlantWater (PW). Shoot length is presented as 1) average length of the five tallest shoots, measured in the mesocosms during the growth phase, and 2) as average shoot length of the harvested plants.

Plant development	Sediment (SED)	Water level (WL)	Plant species (PL)	SED*WL	SED*PL	WL*PL	SED*WL*PL
# germinated seeds	*	NS	***	NS	*	NS	NS
# shoots	NS	**	**	NS	NS	**	NS
Shoot length (5 tallest shoots)	***	NS	NS	NS	**	NS	NS
Average shoot length	***	***	**	NS	*	***	NS
Total biomass shoots	***	***	***	NS	NS	NS	NS
Total biomass roots	***	NS	NS	NS	*	NS	NS

NS = not significant.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

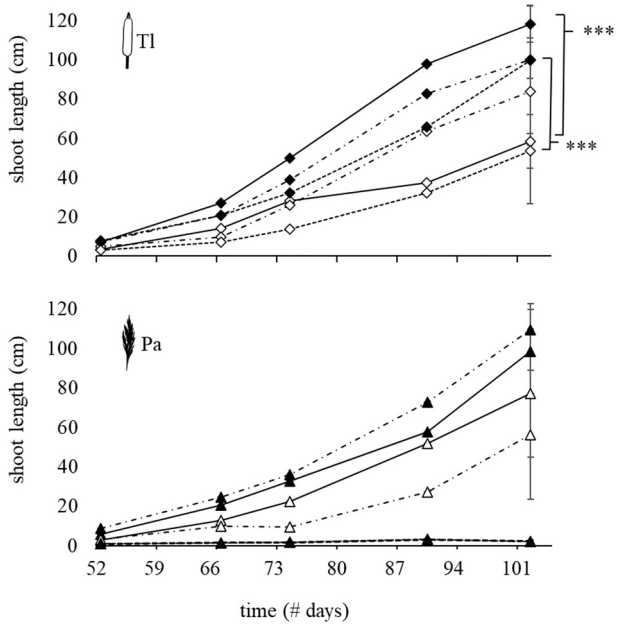


Fig. 4. Average shoot length (SD added to last in situ measurement) of the five tallest shoots for *Typha latifolia* (top panel) and *Phragmites australis* (lower panel) under inundated (dotted lines), saturated (interrupted lines) and moist (solid lines) conditions on clay (open symbols) and mud (filled symbols). Asterisks refer to significant differences between mesocosms containing mud and clay sediment under comparable plant and water level treatments ($n = 5$).

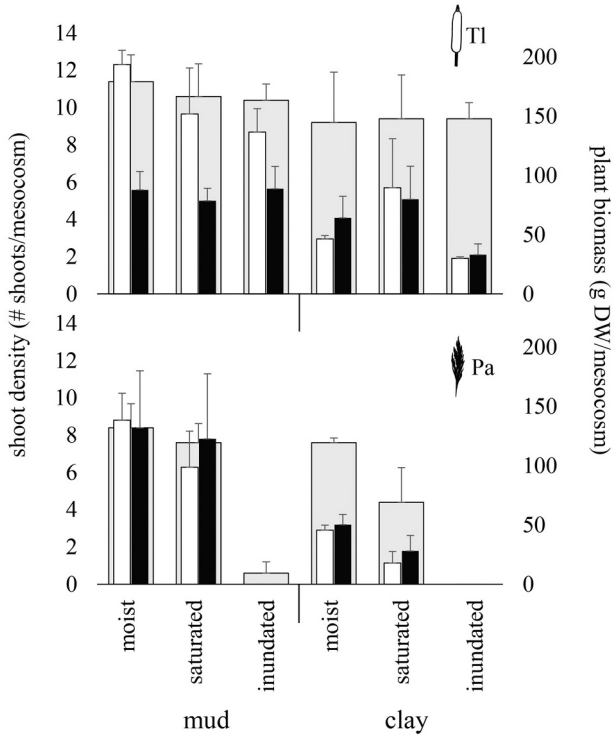


Fig. 5. Average shoot density (dotted bars), and biomass of shoots (white bars) and belowground parts (black bars) for *Typha latifolia* (top panel) and *Phragmites australis* (lower panel) after 120 days growth on dredged mud and clay sediments under inundated, saturated and moist conditions. (±SE, $n = 5$).

pH, conductivity, light regime, water levels (alternating) temperatures, salinity, and photoperiod (Ekstam et al., 1999, Ekstam and Forseby, 1999, Lombardi et al., 1997)). Differences in germination could be due to differences in sensitivity to these factors between the species. Ekstam and Forseby (2007) for instance found that *P. australis* required a high amplitude (> 10 °C) for germination over the entire range of mean temperatures. Final germination of *T. latifolia* was more sensitive to mean temperature than *P. australis*. The lowered germination success of *T. latifolia* could furthermore be associated with less apparent factors such as higher sulphide levels in mud (Lamers et al., 2012, 2013), lower sediment stability, higher algae concentrations on mud, or differences in germination potential between the two species.

The two types of dredged sediment contained different levels of nutrients. Development of the plants was greater on mud compared to clay, with *T. latifolia* growing larger shoots and both species developing higher biomass of both roots and shoots. However, differences in sediment nutrient levels were not reflected in the nutrient content of the plants. This was also observed by Saaltink et al. (2018), who found no differences in shoot N and P content in *P. australis* growing on sediments

Table 3
Plant nutrient concentrations (g / kg dry plant material) for carbon (C), nitrogen (N) and phosphorus (P) in *Typha latifolia* and *Phragmites australis* grown on the dredged sediments clay and mud. Since there was no effect of water level on plant nutrient concentration, these treatments were pooled ($n = 15$, only for *P. australis* on clay $n = 10$).

	T. latifolia				*P. australis*			
	Clay		Mud		Clay		Mud	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
C	428.1	12.6	455.9	4.9	448.9	3.2	456.2	6.0
N	8.7	1.4	10.8	2.1	8.7	2.3	16.4	6.1
P	3.0	0.5	2.5	0.5	1.8	0.2	1.9	0.6

comparable to those used in the present study. As the experiment did not significantly alter the sediments' nitrogen and phosphorous content, plant development did not exhaust the nutrient concentrations in the

sediments. Therefore, nutrient concentrations in these sediments were probably not limiting plant growth and development. The differences in plant development on mud compared to clay did not result from nutrient limitation on clay, but might be related to nutrient uptake processes or a response to elevated nutrient levels. Literature for instance shows that responses of *P. australis* and *T. latifolia* to elevated nutrient levels include: increasing length, number of shoots, shoot biomass, and a lower shoots/below ground biomass ratio (Romero et al., 1999; Saltonstall and Stevenson, 2007; Steinbachová-Vojtíšková et al., 2006; Wetzel and Van Der Valk, 1998). *P. australis* seems capable of acclimating to low nutrient availability by increasing its affinity for ammonium uptake and is able to adapt to a wide range of growing conditions (Romero et al., 1999), becoming a strong competitor when invading new areas (Chambers et al., 2003; Saltonstall and Stevenson, 2007). However, its sensibility to high salinity and sulphide concentrations can hinder its development (Chambers et al., 2003). Steinbachová-Vojtíšková et al. (2006) found that for *T. latifolia*, elevated nutrient levels tend to reduce allocation to roots. Low allocation to roots, resulting in lesser root length and biomass, has implications for the contribution potential of plants to soil formation and stabilization in wetlands. When comparing root/shoot biomass ratio for both sediment treatments, *T. latifolia* did develop relatively more shoot than root biomass on the more nutrient rich mud. However, as root biomass was higher on mud than root biomass on clay, no implications of preferential allocation for soil stabilization are expected.

4.2. The influence of water level on plant development

Applying the water level treatments after germination had initiated, prevented seeds from floating to the water surface (Meng et al., 2016; Van Leeuwen et al., 2014). In permanently inundated zones in created wetlands, seeds would probably have less chances to germinate and attach to the sediment. *T. latifolia* seeds adapt to aquatic conditions (Meng et al., 2016) and during early development no effects of water level on plant growth and development were found. Plant development in *P. australis* was rare under inundated conditions. This indicates that *P. australis* is not only sensitive for inundated conditions during germination (Meng et al., 2016; Saltonstall and Stevenson, 2007), but also during early development of plants. Since *P. australis* was observed to develop well under periodically inundated conditions on the same sediments (Saaltink et al., 2018), we presume that the permanent nature of the inundated conditions, combined with an increase of suspended algae, could have been detrimental for further development of *P. australis*. Although our experiment indicated no limitation of nutrients for plant growth and development, studies on human-induced cycles of drawdown and rewetting of comparable substrates found strong linkages between element cycles and interactions of nitrogen, phosphor, iron, sulphur and calcium under changing redox conditions (Vonk et al., 2017; Saaltink et al., 2018), as observed in general in sediments from marine origin (Burdige, 2006).

4.3. Use of dredged sediments to construct wetlands

We showed that wetland plants can successfully germinate and mature on dredged sediments in mesocosms. At constructed wetlands in situ, water dynamics and turbulence may provide additional difficulties for plants to maintain themselves (Redelstein et al., 2018). Turbulence induced resuspension and settlement of fine sediment particles can smother plants and decline light availability in the benthic zone. This is especially relevant for the fine-grained mud sediment present in Lake Markermeer (Vijverberg et al., 2011). The developmental stage of the plant at which disturbances like resuspension or algal blooms occur, therefore determines the potential resistance of the plants to these disturbances. Also, small differences in elevation within a developed wetland could create locations with low water levels or temporal inundation, providing opportunities for plants to escape risks associated with inundated conditions. This can make a difference in terms of successful vegetation development, especially for *P. australis*. Plant root structures on the other hand facilitate microtopographic development, which will increase landscape heterogeneity on the longer term. Shafer and Streever (2000) found that it would take decades of time for dredged material marshes to develop below ground plant biomass comparable to that of natural marshes. The clay already showed more differences in structure and height in mesocosms compared to the mud, potentially creating a more heterogeneous micro-landscape within constructed wetlands. The mud on the other hand facilitated biofilm development, which can contribute to nutrient availability for grazing macroinvertebrates and affect microbial processes (Mermillod-Blondin et al., 2018), but may also clog interstitial pores (Fetzer et al., 2017). Shafer and Streever (2000) also mention the importance of allowing variation in the elevation profile (micro- or meso-topography) for wetland development. They found that on average, dredged material constructed marshes had fewer ponds and flooded depressions than natural marshes, despite having equal potential to develop elevations. They advise not to overbuild protection structures.

Managing water levels during early-stage development of constructed wetlands for creating (temporal) saturated or inundated conditions, may provide opportunities to influence pioneer vegetation composition. Ecosystem development on constructed wetlands can therefore be manipulated by adequate management of the hydrological regime (Saaltink et al., 2018). Next to hydrological effects, biological interactions (e.g. grazing on seedlings and plants; Bakker et al., 2016) will have a strong impact on wetland development as well. In our study, occasional biological activities or events, such as Diptera larvae developing in the soil and temporal algae blooms, showed a profound effect on plants in early development stages. Plants that had developed more biomass and roots were less affected. It is assumable that local biological interactions or events eventually add to heterogeneity in wetlands as succession trajectories may locally be affected by biological events, thus facilitating different succession states to occur as patches within the wetland.

Our short-term study on the use of dredged sediments for the development of wetland plants gives an indication for initial plant development during the pioneer phase of constructed dredged material wetland. Development, competition and succession of functional plant groups are long term processes. . Stefanik and Mitsch (2012) therefore recommend extended monitoring for at least 10–15 years after construction of wetlands to allow the structural characteristics of the wetland to stabilize before determining if the mitigation project was a success. Also, observed differences in physical and chemical characteristics of the dredged sediments will have impact on the long-term development of the constructed wetland. Even after conversion into freshwater lakes almost a century ago (1932), the dredged sediments from the constructed delta lakes in the IJsselmeer region, the Netherlands, still have characteristics resembling marine sediments (this study, Vonk et al., 2017). These slow changes in sediment conditions indicate that characteristics of the construction sediments will have long-lasting influences on biogeochemical processes of the ecosystem in which they are introduced. When constructing wetlands from these sediment, the character of the sediments will probably affect wetland development processes, depending on the impact of plant activity and soil formation on the sediment. Draining dredged sediments to construct saturated or terrestrial soils from aquatic sediments could also give rise to risks. For example, the sulphur level and pyrite content of the muddy sediment in our experiment classifies it as sediment that could potentially evolve into acid-sulphate soil (Van Breemen, 2015). When these soils are exposed to air, due to drainage or decreasing water levels, the reduced iron sulphide minerals can oxidise and the soil can acidify (pH < 4) due to the formation of sulphuric acid and form sulphuric soils (pH < 4) (Fanning, 1988). These processes can have a large impact on ecology. In our experiment acidification processes did not occur; pH measured 8.5 to 9 and conductivity remained low within the range

characteristic for fresh water. Still, the possible risk of acidification should be considered when applied on a larger scale. In addition to this, co-occurring species (e.g. primary producers, consumers and bioturbators) may affect the trajectory of macrophyte development at the landscape scale (e.g. Legault et al., 2018), which makes long-term developments of constructed wetlands in degraded delta lakes difficult to assess without proper monitoring.

5. Conclusions

We showed that dredged sediments, consisting of former marine deposits, are suitable for macrophyte vegetation development. Both plant species developed significantly more biomass and larger shoots growing on mud compared to growing on clay. Overall, *T. latifolia* development was more strongly influenced by sediment composition than *P. australis*. *P. australis* was more vulnerable to higher water levels during early stages of development, and barely developed shoots under inundated conditions. The mud sediment contained more nutrients than the clay sediment, but nutrient content in both sediments were sufficient to facilitate plant development. After harvesting, the phosphorous content of the sediments and in the plants did not show signs of depletion, indicating that phosphorous availability was not a limiting factor.

CRediT authorship contribution statement

M.C. van Riel: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft. **J.A. Vonk:** Writing – original draft, Visualization. **R.C.M. Verdonschot:** Conceptualization, Writing – review & editing. **J.F. Ferrús Muñoz:** Investigation, Formal analysis. **P.F.M. Verdonschot:** Conceptualization, Methodology, 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.

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