



# Species selection and assessment of eco-engineering effects of seedlings for biogeomorphological landscape experiments

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Received 24 December 2017; Revised 26 June 2019; Accepted 3 July 2019

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## ESPL

Earth Surface Processes and Landforms

**ABSTRACT:** Landscape experiments of fluvial environments such as rivers and deltas are often conducted with live seedlings to investigate effects of biogeomorphological interactions on morphology and stratigraphy. However, such experiments have been limited to a single species, usually alfalfa (*Medicago sativa*), whereas important environments in nature have many different vegetation types and eco-engineering effects. Landscape experimentation would therefore benefit from a larger choice of tested plant species. For the purpose of experimental design our objective was to identify fast-germinating and fast-growing species and determine their sensitivity to flow conditions during and after settling, their maximum growth, hydraulic resistance and added bank strength. We tested germination time and seedling growth rate of 18 candidate species with readily available seeds that are fast growing and occur at waterlines, plus *Medicago sativa* as a control. We selected five species that germinate and develop within days and measured properties and eco-engineering effects depending on plant age and density, targeting typical experimental conditions of 0–0.3 m/s flow velocity and 0–30 mm water depth. Tested eco-engineering effects include bank strength and flow resistance. We found that *Rumex hydrolapathum* can represent riparian trees. The much smaller *Veronica beccabunga* and *Lotus pedunculatus* can represent grass and saltmarsh species as they grow in dense patches with high flow resistance but are readily erodible. *Sorghum bicolor* grows into tall, straight shoots, which add significantly to bank strength, but adds little flow resistance and may represent sparse hardwood trees. *Medicago sativa* also grows densely under water, suggesting a use for mangroves and perhaps peat. In stronger and deeper flows the application of all species changes accordingly. These species can now be used in a range of landscape experiments to investigate combined effects on living landscape patterns and possible facilitation between species. The testing and treatment methodology can be applied to new species and other laboratory conditions. © 2019 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

**KEYWORDS:** bank strength; biogeomorphology; flow resistance; landscape experiments; plant species

## Introduction

Many landscapes on planet Earth are formed by a suite of physical and biological processes, and the greatest challenges lie in understanding how biogeomorphological interactions lead to emergent patterns and dynamics that differ from those either dominated by life, such as tropical rainforest and peat, or pure morphodynamics devoid of life, such as alluvial fans on planet Mars. Eco-engineering species, which modify their physical environment such that conditions become favourable to further settling and establishment of other species, are of particular interest (Jones *et al.*, 1994; Corenblit *et al.*, 2011; Gurnell *et al.*, 2012) (Table I). While a great number of field studies have been conducted (Leonard and Luther, 1995; Gurnell and Petts, 2006; Vandenbruwaene *et al.*, 2011) and model development with interactions of species and hydromorphodynamics is intensifying

(Coco *et al.*, 2013; Solari *et al.*, 2016; Nardin *et al.*, 2016; Fagherazzi *et al.*, 2012), morphodynamic landscape experiments with live vegetation lag behind in the representation of eco-engineering species. To avoid practical difficulties of real plants in scaled experiments, some experimenters used plastic vegetation (e.g. Luhar and Nepf, 2011; Vargas-Luna *et al.*, 2015) but this removes the mutual interaction of biotic and physical processes. While both numerical modelling and ‘physical modelling’ of plants have had their use, the investigation of eco-engineering effects implies that new individuals and new species can settle, grow and be subject to the various causes of mortality through ageing and environmental stresses (van Oorschot *et al.*, 2016). This means that experiments with live vegetation potentially lead to novel insights into channel-scale, bar-scale and reach-scale eco-engineering effects, and indeed significant understanding was gained in river

**Table 1.** Examples of fluvial and coastal vegetation types and their habitats with distinct eco-engineering effects that we aimed to reproduce

Eco-engineering landscape	Habitat	Eco-engineering effects	Example species
Riparian vegetation (trees and mangroves)	Intertidal area up to higher bathymetry	Soil enforcement due to rooting flow focusing/retardation (Corenblit <i>et al.</i> , 2007)	<i>Avicenna</i> , <i>Salix</i>
Saltmarsh	Mean water level up to high tide	Soil enforcement substantial flow retardation (Schwarz <i>et al.</i> , 2018)	<i>Spartina</i> , <i>Juncus</i>
Freshwater floodplain	Adjacent to channel up to highest flooded areas	Marsh-like effects for grasses; riparian type effects for trees (van Oorschot <i>et al.</i> , 2016)	<i>Phragmites</i> , <i>Typha</i>

experiments with live vegetation (Gran and Paola, 2001; Coulthard, 2005; Braudrick *et al.*, 2009; Bertoldi *et al.*, 2009; van Dijk *et al.*, 2013) (see, for review, Kleinhans *et al.*, 2015).

Here we investigate methods to select and scale live vegetation for use in morphodynamic landscape experiments of fans, deltas, rivers, estuaries and tidal basins, which were often conducted without vegetation (e.g. Stefanon *et al.*, 2010). We aim to find vegetation species suitable for these large-scale experiments with dynamic, evolving landscapes of channels and floodplain, which are characterized by small water depths, and we focus on (partially) emergent vegetation. These experiments are typically conducted to investigate biogeomorphological patterns, dynamics and resulting stratigraphy at the scale of bars, channels, meander or braid belts and larger phenomena, meaning that experiments are typically between  $10^3$  and  $10^5$  times smaller and faster than the simulated systems in nature (Kleinhans *et al.*, 2015). In this paper, 'suitability for experiments' is particularly targeting the landscape experiments. However, the types of auxiliary experiments conducted here to test specific vegetation properties and effects can also be set up for engineering scale experiments and full-scale flume experiments that target specific eco-engineering effects. Vegetation interacts with hydromorphodynamics through a large number of processes (Corenblit *et al.*, 2011; van Oorschot *et al.*, 2016; Kleinhans *et al.*, 2018; Schwarz *et al.*, 2018). The most important at the aforementioned scales are increased hydraulic resistance and increased strength of the bed, banks and floodplain surface. However, individual riparian trees cannot be scaled down a factor of 1000 or more, let alone small species such as grasses and reeds. The challenge in using vegetation for hydromorphological landscape experiments at such scales is thus to scale their effects on the hydromorphodynamics such that these fit the experimental flow velocities, water depths, sediment strengths and bank strengths (Kleinhans *et al.*, 2015). In other words, experiments are considered successful when similarity of relevant processes is obtained (Gran and Paola, 2001; Coulthard, 2005; Tal and Paola, 2007; Paola *et al.*, 2009). This may mean that individual plants in experiments represent the effects of a large number of plants (Kleinhans *et al.*, 2015).

Thus far, most experiments with living vegetation were conducted with alfalfa (*Medicago sativa*) sprouts, which, as individual plants, are considerably larger on the experimental scale than riparian trees in nature. However, as a vegetation cover they have interesting morphological effects (Braudrick *et al.*, 2009; Tal and Paola, 2010; Perona *et al.*, 2012; van Dijk *et al.*, 2013; Crouzy *et al.*, 2013) that are mainly determined by the easily measurable quantities spatial vegetation density (Nepf, 1999; Gran and Paola, 2001; Zong and Nepf, 2010; Nepf, 2012a, 2012b) and root length (Edmaier *et al.*, 2014). Here, vegetation density determines flow resistance and the degree to which the flow is deflected elsewhere, away from the vegetation, and root length determines the

shear stress that the vegetation can survive and the strength the vegetation adds to the banks. Furthermore, the seed distribution in all experiments except van Dijk *et al.*, (2013) was done manually. However, van Dijk *et al.*, (2013) showed that morphological effects of vegetation differed considerably when spread hydrochorously – that is, spread by the water from the upstream water and sediment source. These findings illustrate that settling, growth and mortality all have important effects in experiments, as also demonstrated in models (van Oorschot *et al.*, 2016).

Since the discovery that alfalfa (*Medicago sativa*) can be used in river experiments (Gran and Paola, 2001), most further research has been conducted with this species (Braudrick *et al.*, 2009; Tal and Paola, 2010; Perona *et al.*, 2012). Notable exceptions, all with larger seeds and plants, were Perona *et al.*, (2012) and Clarke (2014), who seeded oats (*Avena sativa*) to represent riparian trees, and Coulthard (2005) and Rominger *et al.*, (2010), who planted several bedding plant species that represented entire patches of vegetation. The advantages of alfalfa over many other species are its fast germination and high germination fraction, especially after pre-soaking treatment, and its resilience to changes in temperature, light and water availability (Clarke, 2014). Furthermore the characteristics of the roots are considered similar to juvenile riparian vegetation in nature. As the roots grow there is an increase in the forces plants can withstand (Edmaier *et al.*, 2014). Such forces include the flow on the plants that may lead to uprooting, the flow on the rooted soil that may lead to erosion, and the weight of the oversteepened bank that is partly carried by the bundle of roots (e.g. Simon and Collinson, 2002). However, in order for the roots to have a significant effect on bank retreat, but not stabilize the banks completely, the roots should neither be much shorter than channel depth nor much longer. This means that the plant species and the scale of the experiment need to match, which suggests a necessity to work with small juveniles or sprouts.

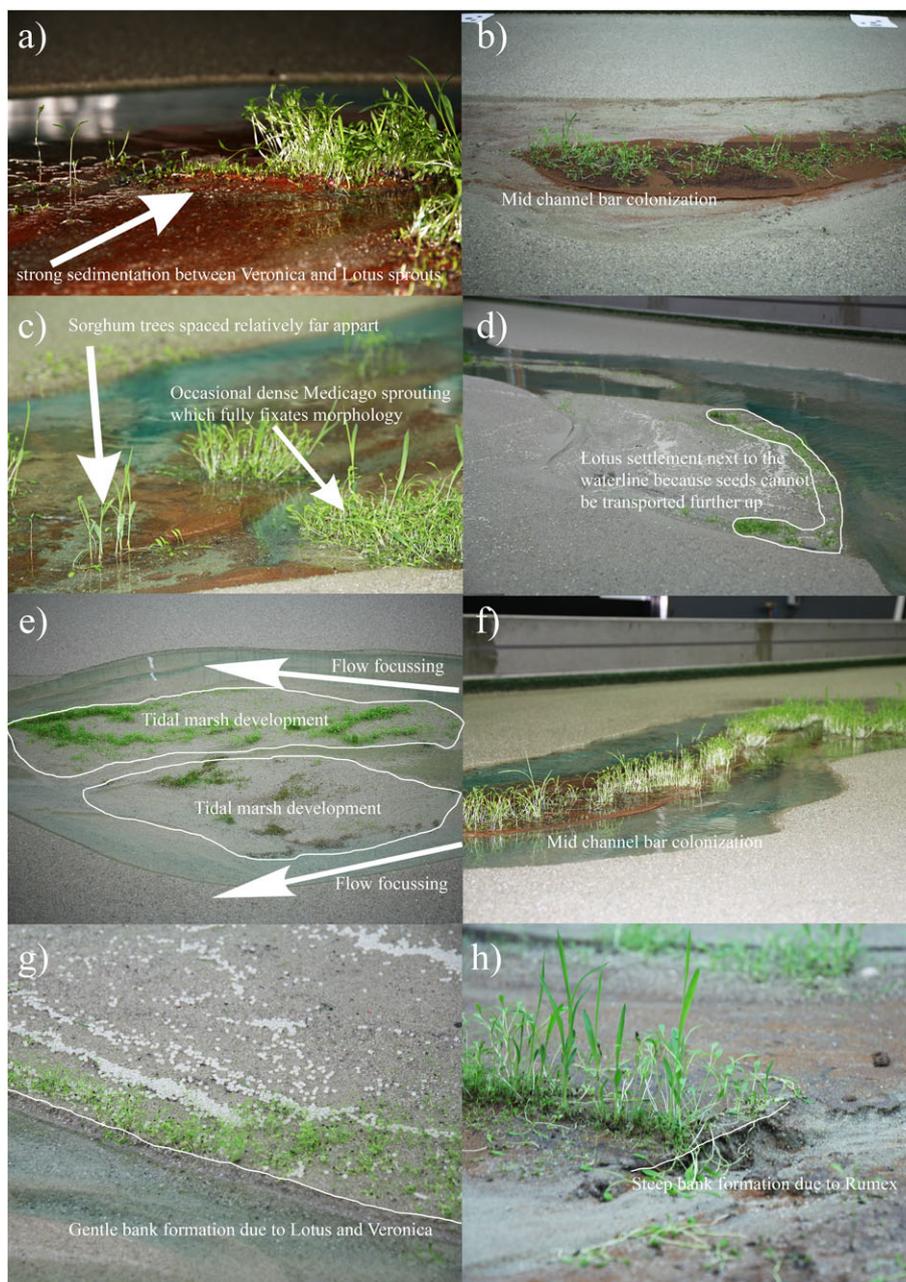
In nature, however, there are many different habitats with types of vegetation that differ considerably in characteristics and eco-engineering effects from riparian trees (Corenblit *et al.*, 2011; Gurnell *et al.*, 2012; Bouma *et al.*, 2014). For rivers and estuaries these include salt marshes with, for example, *Spartina* species, mangrove forests including *Avicennia* species, riparian forests with, for example, *Salicaceae* species and vegetated deltas with *Nelumbo* species. These species differ largely in how they affect biogeomorphodynamics: salt marshes occur in the intertidal area and can be alternately submerged and emerged; mangroves are emergent but grow in the intertidal area; riparian forests are emergent and grow in general above the waterline; hile vegetated deltas also have macrophytes including floating vegetation. The eco-engineering species in these environments have starkly different settling conditions, inundation and uprooting tolerance, rooting density and added bank strength and flow

resistance. This leads to the question of how we can represent these different vegetation types in laboratory experiments. Given the presence of hundreds of thousands of plant species on the planet, a wider selection of experimentally applicable species should be possible and of use in a range of biogeomorphological experiments.

The main advance in using live vegetation in physical experiments is that they allow study of two-way interactions between hydromorphology and biology. Plants may settle and develop somewhere in the experimental system as a function of initial hydromorphological conditions and controlled boundary conditions. Through their interaction with the flow they affect sedimentation patterns and therefore alter the landscape. These vegetation-driven changes in the landscape either favour or hinder new plant development in the next seeding cycle, and possibly facilitate other species that would otherwise not settle there. Figure 1 is an illustration of the biogeomorphological

patterns that emerge when different vegetation species are combined in tidal experiments (Kleinhans *et al.*, 2017a; Braat *et al.*, 2018; Leuven *et al.*, 2018) with scaling, sediment and vegetation treatment similar to that in van Dijk *et al.*, (2013). Such experiments need to be developed in the future, but need a starting point of systematically analysed sensitivity of species to landscape experiment conditions and effects of the species on critical aspects of the hydromorphodynamics.

The objective of this paper is therefore to find and test several vegetation species that can represent a range of different settling conditions and tolerance against inundation and erosion in laboratory experiments, and have different eco-engineering effects, in particular enhanced bank strength by rooting and hydraulic resistance depending on sprout size and settling density. In this sense both the methods and the results are intended to be a benchmark for physical modelling with vegetation. The results may aid in the choice between species in an



**Figure 1.** Examples of vegetation settling locations and morphological effects of five vegetation species in tidal pilot experiments, not further described here, in a tilting flume described in Kleinhans *et al.* (2017a). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

experiment, and the suite of methods can efficiently be reused to test the same species under different laboratory conditions and can be used to test new species for other types of experiments.

## Methods

The study was set up as follows. First we created a large list of candidate species based on roughly known germination times, size, preference to grow in wet conditions and commercial availability. From this list we selected fast-growing species for practical reasons of fast progress of experiments, in which the duration of plant germination is time consuming. Then the settling velocity of the seeds and potential eco-engineering effects of selected species were tested in a set of four experiments under hydromorphological conditions of roughly 5–30 mm water depth and scale typical for landscape experiments. We measured seed settling velocities for use as an indicator of seed transport in suspension, sensitivity of seedlings to inundation depth in terms of sprouting, hydraulic resistance caused by seedling stems, and reduction of bank erosion caused by rooting. Finally, we discuss the environments that these species can represent in their application in various landscape experiments.

There are some limitations to this study. First, the experiments are all conducted for a specific range of hydromorphodynamic conditions in landscape experiments, meaning water depths of 5–30 mm in a number of laboratories. Second, the transport of seeds is based on settling velocity experiments and seed characteristics. We used these to interpret likely seed transport and establishment patterns, but these need to be studied in actual landscape-scale experiments, and modified in other types of experiments such as distorted engineering scale models and flume experiments targeting specific biophysical feedbacks. While trial and error in such large experiments are at the cost of considerable experimental time, the proposed methods here are fast and may well be applicable to many different experimental settings and species.

## Selection of species

Our first selection of 19 vegetation species was based on three criteria: they should be able to grow near the waterline in nature, the species need to be fast growers, and seeds need to be available for purchase in quantity (Table II). This limited our selection to species well known to our botanical gardens, which is appropriate for practical reasons but also suggests that further searches for useful species likely yield a longer list. The growth rate of seedlings is essential in experimental design, where the characteristic timescale at which a natural stress such as a flow event can be applied needs to be related to the characteristic timescale of vegetation development (Tal and Paola, 2007; Perona *et al.*, 2012; Kleinhans *et al.*, 2015):

$$\tau = \frac{T_{\text{develop}}}{T_{\text{disturbance}}} \quad (1)$$

where  $T$  is a timescale,  $\tau > 1$  means that vegetation is likely to survive typical disturbances and  $\tau < 1$  means higher vegetation mortality. This relative timescale indicates how long experiments have to be paused after seeding events, which typically is the most important limiting factor in the duration of experiments. The first 19 species were therefore tested on how they develop with respect to the water depth and how fast they grow. We also sought a large range in seed size, or diameter, between species, because this is an indicator of the potential length that the plants

**Table II.** The 19 candidate species in which growth rate was measured, with abbreviations used in this paper and with typical environments. A few more species tested initially, shown in Figure 6, were not suitable or readily available.

Species name	Abbrev.	Natural environment
<i>Beta vulgaris rubra</i>	BV	Coastal grasslands, salt marshes
<i>Brassica oleracea</i>		
<i>botrytis cymosa</i>	BO	(Silty) coastal areas
<i>Brassica rapa</i>	BR	Waterfronts, fallow land
		Swamps, waterfronts, grassland, dikes
<i>Lotus pedunculatus</i>	LP	
<i>Lycopus europaeus</i>	LE	Swamps, ditches, moist forest
<i>Lythrum salicaria</i>	LS	Marshes, floodplains
		Grassland, fallow land, waterfronts
<i>Medicago sativa</i>	MeS	
<i>Myosotis scorpioides</i>	MyS	Swamps, waterfronts
		Moist grassland, ditches, moist forests
<i>Persicaria bistorta</i>	PB	
<i>Phacelia tanacetifolia</i>	PT	Gardens, roadsides, wasteland
		Moist sandy loams, cultivated only
<i>Raphanus sativus</i>	RS	
<i>Rumex hydrolapathum</i>	RH	Swamps, waterfronts, floodplains
<i>Sorghum bicolor</i>	SB	Hot arid or semi-arid areas
		Moist well-drained soils, cultivated only
<i>Spinacia oleracea</i>	SO	
<i>Tagetes patula</i>	TP	Pine-oak forest
<i>Typha latifolia</i>	TL	Wetlands
		Waterfronts, marshes, grasslands, wet grounds
<i>Veronica beccabunga</i>	VB	
<i>Vigna radiata</i>	VR	Moist grasslands

attain without nutrients (Leishman *et al.*, 2000) and because seed size likely affects the transport mode in the experiments.

To test the suitability of the species for time-limited experiments, we conducted the following experiment. Of each species, three pots with 10 seeds on a sand surface were prepared. The sand in all our experiments was a coarse, poorly sorted mixture with a D50 of 0.55 mm, a D10 of 0.32 mm and a D90 of 1.2 mm, and, due to the wet separation process by the supplier, entirely devoid of silt, clay and nutrients. This sand was designed to prevent experimental flow from being hydraulically smooth and forming scour holes and ripples (Kleinhans *et al.*, 2017b). The water levels in the pots were controlled, as described later, at 10 mm below the bed surface, at the bed surface and 10 mm above the bed surface. The seeds in these pots were allowed to grow for 15 days. The experiment was conducted in May and June in a greenhouse with a naturally varying temperature and light intensity in the Netherlands.

During the experiment we measured shoot development during 15 days, and root length after 15 days, for all plants. This provided insight into the development time of the plants and their dimensions. We also tested the effect of a cold treatment (Clarke, 2014), but found no difference except for *Lycopus europaeus*, *Myosotis scorpioides*, *Typha latifolia* (LE, MyS and TL), which benefited from the treatment. Based on the results and criteria, five promising species were selected for further investigation under more controlled conditions. The other experiments described below were performed only with the five selected species.

## Transport mode of seeds in experimental flows

Following selection of the most promising species, the characteristics important for hydrochorous transport of the seeds were determined. These are characterized by the Rouse number and

the particle Reynolds number as indicators of particle mobility and settling out of the water column. In nature, seed buoyancy affects the seed dispersal patterns (Sarneel *et al.*, 2014). In experiments, however, seeds should be pre-soaked when they are spread hydrochorously; otherwise most of the seeds leave the flume floating without settling (Clarke, 2014). As the seeds are no longer buoyant after pre-soaking, the degree of suspension of the seeds determines whether the seeds deposit from bedload close to the main channel or are carried further up on the floodplain in suspension. This points to the need for laboratory protocols to standardize soaking and seeding procedures in a given experimental setting.

We use the Rouse number  $Z$  as an indication of whether a particle is transported as bedload ( $Z > 2.5$ ), suspended load ( $0.8 < Z < 1.2$ ) or washload ( $Z < 0.8$ ) for given flow conditions (Cheng and Chiew, 1999):

$$Z = \frac{w_s}{\kappa u_*} \quad (2)$$

where  $w_s$  is the particle settling velocity in still water,  $\kappa = 0.4$  is the von Karman constant and  $u_* = \sqrt{ghS}$  is the shear velocity, assuming normal flow, where  $g$  is the gravitational acceleration ( $\text{m/s}^2$ ),  $h$  is water depth (m) and  $S$  is slope (m/m). The particle Reynolds number is a measure for the behaviour of the flow around the seeds with diameter  $D_s$ , which affects the settling behaviour (Cheng and Chiew, 1999):

$$\text{Re}_p = \frac{D_s w_s}{\nu} \quad (3)$$

where  $\nu$  is dynamic viscosity ( $\nu \approx 1.16 \times 10^{-6} \text{ m}^2/\text{s}$  for lab temperature). A particle Reynolds number of  $\text{Re}_p > 10$  means turbulent flow around the seed,  $1 < \text{Re}_p < 10$  means transitional conditions and  $\text{Re}_p < 1$  means laminar flow conditions. To be able to use the particle Reynolds number we measured seed diameter along the longitudinal axis with a digital Vernier caliper.

Both the particle Reynolds number and the Rouse number are a function of the particle settling velocity. This was determined in a settling tube. A 0.36 m tall glass cylinder of 0.05 m diameter was filled with tap water at about 11° C. Low numbers of seeds, pre-soaked for 24 hours, were released and the time to reach the bottom was recorded with a stopwatch. To account for measurement errors the measurements were repeated eight times.

### Sensitivity to water depth in the sprouting phase

For plants to occupy the range of physical environments in experiments, a high sensitivity to shallow water depth is needed. In most experiments the plants should not settle and develop on the main channel floor, but rather at the water line and above it as riparian trees (Francis *et al.*, 2006), or slightly below it in mangrove (Krauss *et al.*, 2008), reed and saltmarsh settings

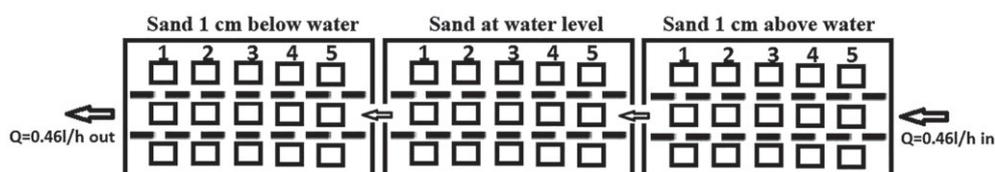
(Craft *et al.*, 2009; Schwarz *et al.*, 2018). For the plants to differentiate between these types of natural vegetation they should develop differently when grown under different inundation conditions. Therefore, we test sprouting and development of the plant length and diameter for a typical range of bed elevations in landscape experiments from above to below the average water surface.

A series of plant pots with controlled water level were prepared to test the sensitivity of the species to inundation depth (Figure 2). As we used washed, poorly sorted sand without nutrients and without silt or finer sediment, the sprouts are limited in growth by the nutrients stored in the seed itself. The plant seeds ranged from slightly smaller than the median grain size (*Veronica beccabunga*) up to 10 times larger (*Sorghum bicolor*). The pots were filled with a sand layer of 70 mm, deeper than the longest roots, and were placed in trays with a water height of 60, 70 or 80 mm. This provided either submerged beds with the water level above the sand surface, in which case the sand was 10 mm below the water surface, fully saturated beds with water, sand and seeds at the same level, or beds that were wet because of the capillary rise of water that was 10 mm below the surface. The water level in the trays was kept constant by a constant head system with an overflow and pump to ensure oxygen-rich conditions and negligible flow. Light intensity was kept constant at 180 lux and the temperature was  $22.5 \pm 0.5^\circ \text{C}$ . Additionally, chlorine and an anti-algae product were added to reduce the growth of algae, biofilms and fungi, which is also of importance in flume experiments when these are not the scope of the research and considered pests. The effective chemical in the anti-algae was didecylidimethylammonium chloride, which was applied at  $1.77 \text{ g/m}^3$ . Preliminary tests showed that more seeds sprouted when these chemicals were added, and no difference in sprouting was found between this dose and higher concentrations.

We measured the fraction of seeds that germinated on a daily basis as well as shoot length and diameter. Length and diameter were measured with a digital Vernier calliper. After 14 days the plants were carefully removed from the soil and root length was measured. Unlike shoots, roots are thus only measured at the end of the experiment. Figure 3 shows images of the roots and shoots after 14 days of growth of the five plants selected for more detailed experiments. To characterize the plant growth we compared sprout growth with the typical time dependence of plant growth, and fitted a sigmoidal function by least squares (Yin *et al.*, 2003):

$$w = w_{\max} \left( 1 + \frac{t_e - t}{t_e - t_m} \right) \left( \frac{t}{t_e} \right)^{\frac{t_e}{t_e - t_m}} \quad (4)$$

where  $w$  is the biomass of a plant, which we substituted with measured length at time  $t$ ,  $w_{\max}$  is the maximum biomass, which we substituted with maximum sprout length obtained without nutrients,  $t_e$  is the time before the maximum length was reached, and  $t_m$  is the time when the growth speed was greatest. Therefore, we can easily determine the time of



**Figure 2.** Experimental setup to test water-level sensitivity during sprouting of five species. The system has one inflow (right), flows over to the other two boxes and has one outflow (left)



**Figure 3.** Images of the five species that were investigated in more detail based on preliminary testing after 14 days of growth: (a) *Lotus pedunculatus*; (b) *Medicago sativa*; (c) *Rumex hydrolapathum*; (d) *Sorghum bicolor*; and (e) *Veronica beccabunga*. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

maximum growth and end of growth of the sprouts for our prescribed laboratory conditions.

$$C_{tot} = \sqrt{\frac{1}{C_b^2 + C_v^2}} \tag{6}$$

**Increase of flow resistance by seedling stems**

Thirdly, we sought dimensions and effective flow resistance of the vegetation which scales reasonably well with flow depth and retardation in rivers, deltas, estuaries and fans. We predicted and measured flow resistance characteristics of the five tested species. Flow resistance expressed as Chezy roughness  $C$  ( $m^{1/2}/s$ ) by emergent vegetation is predicted as follows (Baptist *et al.*, 2007):

$$C_v = \sqrt{\frac{2g}{C_d m D_v h}} \tag{5}$$

where  $C_v$  is the Chezy roughness due to vegetation,  $g$  is the gravitational acceleration,  $C_d \approx 2$  is the drag coefficient, taken somewhat rougher than that of perfect cylinder (Park *et al.*, 1998),  $m$  the stem density ( $m^{-2}$ ),  $D_v$  the stem diameter and  $h$  the water depth. The combined roughness  $C_{tot}$  of bed surface and vegetation is then given by

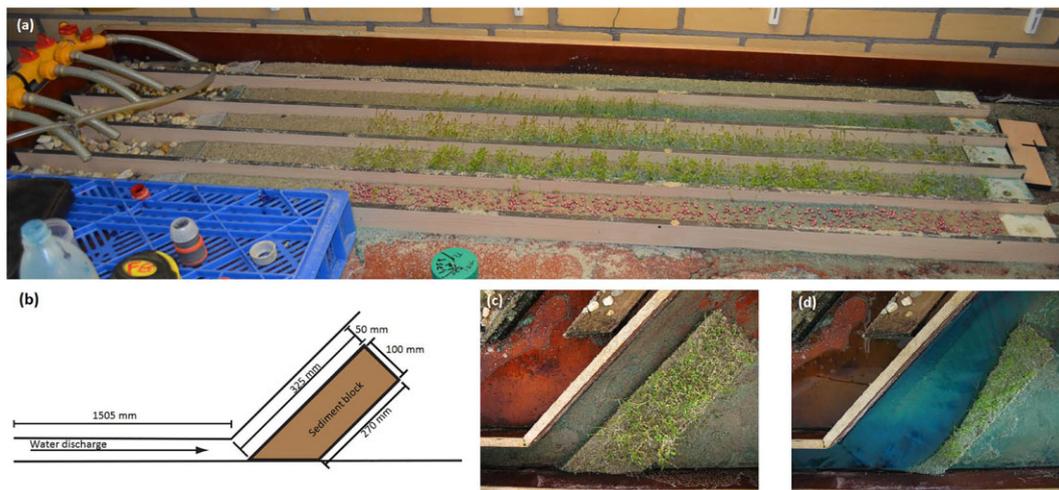
where  $C_b$  is the bed roughness that can be estimated with the Colebrook–White relation for hydraulically smooth flow (Silberman *et al.*, 1963):

$$C_b = 18 \log_{10} \left( \frac{12hu^*}{3.3v} \right) \tag{7}$$

where  $u^*$  the friction velocity obtained through  $\sqrt{ghS}$ . These equations forecast friction values based on geometrical parameters and were compared to the actual Chezy value based on combined water depth and velocity measurements, determined as

$$C = \frac{u}{\sqrt{hs}} \tag{8}$$

As typical water depths in landscape experiments are between 0.005 and 0.03 m (Hoyal and Sheets, 2009; Tal and Paola, 2010; van Dijk *et al.*, 2013; Kleinhans *et al.*, 2014)



**Figure 4.** Experimental setup for hydraulic resistance measurement in straight flumes and Friedkin bank erosion tests. (a) The parallel flumes with uniform vegetation that were used for flow resistance measurements by tracer dye. (b) Schematic representation of the Friedkin flume (based on van Dijk *et al.*, 2013; Kleinhans *et al.*, 2014) with water flowing in from the bottom left corner, approaching the sediment at a 45° angle. (c) Example of vegetated sediment block installed for bank erosion testing. (d) Block with vegetation species during the erosion process, showing coloured water. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

and stem length and thickness are correlated, our plant lengths should not exceed the  $h < 0.03$  m value by much to represent submerged grasses, but can be significantly higher when representing trees.

To determine the actual flow roughness, five small parallel flumes were set up to test the effect of the five vegetation species on flow velocity (Figure 4a). The channels were 70 mm wide and 1.5 m long and had a bed surface gradient of  $S = 0.0083$  m/m. The first 0.3 m of each flume was filled with gravel to break the inflow jet and accelerate formation of a boundary layer. Downstream of this 0.2 m of bare sand was followed by 1 m of vegetated sand. The channels were all filled with 20 mm of sand in which vegetation was seeded, as uniformly as possible by hand, over the last 1 m length at densities of 2 seeds/cm<sup>2</sup>. A discharge of 38 L/h was applied to the channel, which resulted in laminar flow conditions with negligible sand transport and an average water depth of 1.5 mm, which means sidewall effects are negligible (Williams, 1970). At 7, 8 and 9 days after seeding, the flow velocity through the vegetation was measured. This was done by pouring 0.3 cm<sup>3</sup> water with brilliant blue dye, 50 mm before the vegetation started and timing the breakthrough of the front of the dye as it crossed a white boundary just downstream of the vegetation. This measurement was repeated 4 times every day. For the front we took the first crossing in the centre third of the channel. Control experiments without vegetation quantified flow resistance of bare sand and ensured that all five parallel flumes behaved similarly within measurement accuracy.

## Reduction of bank erodibility by rooting

Root length and root density mainly determine the reduction of erodibility of channel banks and the potential for uprooting as shown in past bank erosion experiments (Abernethy and Rutherford, 2001; Pollen, 2007; van Dijk *et al.*, 2013; Edmaier *et al.*, 2014). The work  $W(j)$  required to uproot a seedling has been estimated as (Edmaier *et al.*, 2014)

$$W = aL_{\text{tot}}^{1.4} \quad (9)$$

where  $L_{\text{tot}}$  is the total root length and  $a$  is a calibration parameter based on saturation and sediment grain size, typically about  $3 - 5 \times 10^{-6}$  (Edmaier *et al.*, 2014). A general indicator of the potential for bank undercutting is the rooting depth relative to the bank height. This was experimentally tested and expressed as (Perona *et al.*, 2012)

$$\lambda = \frac{L_{\text{rooting depth}}}{L_{\text{bank height}}} \quad (10)$$

where  $\lambda > 1$  means that vegetation is likely to prevent undercutting and  $\lambda < 1$  means undercutting may occur. This is a simplification of the variability and complexity of natural root systems, but it does show that the direct scaling between bank height and rooting depth affects whether vegetation will reduce bank collapse rates. Sediment may also be removed directly by the turbulent flow from a rooted cutbank, but this erosion is slowed down depending on rooting depth, density and added flow resistance by roots sticking out of the bank.

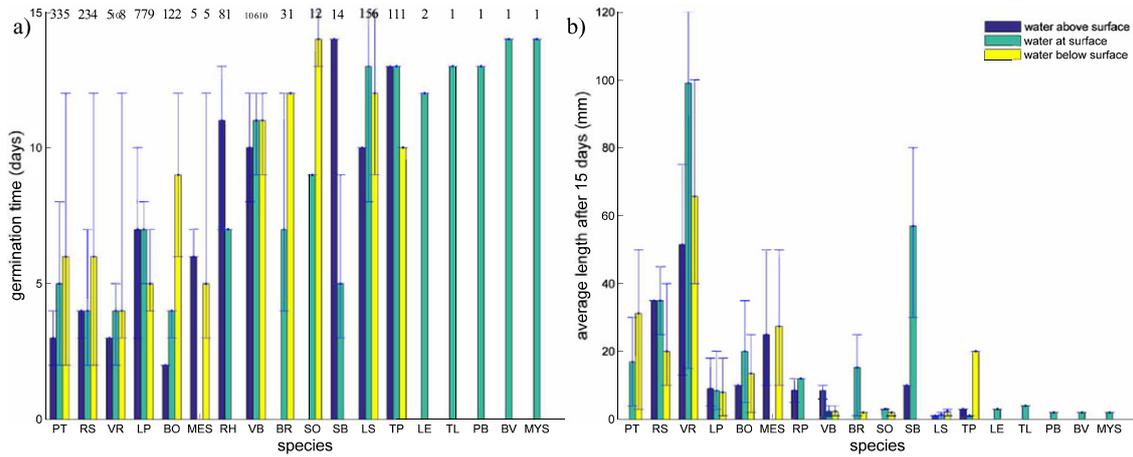
To test the effect of rooting on bank erosion rate an experiment based on Friedkin (1945) and van Dijk *et al.*, (2013) was conducted. We prepared sediment blocks with several vegetation ages similar to van Dijk *et al.*, (2013). These blocks

were placed in our Friedkin flume at the end of a 50 mm wide, 1.5 m long channel with a slope of 0.0083 m/m, where the flow attacks the vegetated sediment block under a 45° angle (Figure 4). The discharge through the channel was 500 L/h. Sand was glued to the bottom of the upstream flume to create hydraulically rough conditions. This setup is different from a landscape experiment and a natural system. However, the fixed and large angle of flow incidence enables us to compare the erosion with and without vegetation in a fully controlled setting and thus isolates the contribution of the vegetation roots to the erosion resistance in a fraction of an hour.

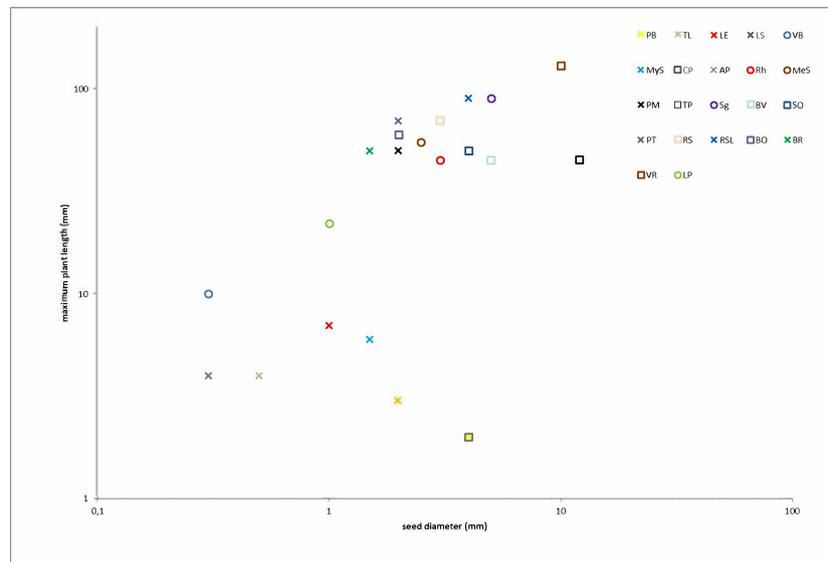
To determine the effect of the vegetation on bank erosion rates we tracked the disappearance of the sediment block by following the position of the bank top line over time. For automatic detection of eroding the bankline the water was coloured by brilliant blue for contrast in overhead photographs taken by a consumer-grade camera every 30 seconds. As the sediment thickness was kept constant in all experiments, we assume that sediment volume is a direct function of bankline position. The bankline was extracted through contrast and pattern recognition by the computer. This, however, resulted in an apparent increase in volume during the first minute of some of the experiments. When the first water reaches the sediment block, sand fell down into the channel, which is analysed as a bankline which progrades into the channel. Following removal of the collapsed sediment, the bank top line indicates volume. Temporal variability is in part caused by these bank collapses and in part by shadows of overhanging vegetation on partly collapsed banks, causing temporary increases of apparent volume. These experiments were conducted for the species *Medicago sativa*, *Rumex hydrolapathum*, *Lotus pedunculatus*, *Veronica beccabunga* and *Sorghum bicolor* at a seeding density of 2 seeds/cm<sup>2</sup> after 7 and after 9 days of growth, which were expected to be of typical density and have clearly measurable effects on the basis of published experiments with *Medicago sativa* (van Dijk *et al.*, 2013; Kleinhans *et al.*, 2015). Duplicates were run to quantify variability, which was found to be acceptably small in van Dijk *et al.*, (2013).

## Results

Germination fraction and time, and the height reached after 15 days, differed between species by a factor up to 10 (Figure 5). If we assume two design criteria, namely the usual experimental water depths and fast germination, approximately half the species required more than a week to germinate and therefore did not meet the requirements for most landscape-scale experiments (Figure 5a). Furthermore, many species remained either extremely small – for example, *Lycopus europaeus* (LE), *Typha latifolia* (TL) – or grew too tall – *Vigna radiata* (VR) – as they would emerge from the deepest channels (Figure 5b). A correlation between seed diameter and stem length exists but shows such a large variation that it is not reliable for prediction (Figure 6). Based on these data, *Medicago sativa* (MeS), *Lotus pedunculatus* (LP) and *Rumex hydrolapathum* (RH) were selected for further analysis. Additionally, a taller and a smaller species were included that germinate fast: *Veronica beccabunga* (VB), because this species grows up to 15 mm, with roots up to 10 mm, which allows undercutting by deeper channels; and *Sorghum bicolor* (SB), because it grows relatively tall. *Sorghum bicolor* was selected over the faster germinating *Vigna radiata* (VR) because the *Vigna radiata* seeds are so large that they cannot easily be transported hydrochorously in morphological experiments with channels up to several centimetres deep.



**Figure 5.** Germination and growth of the candidate species (see Table II for abbreviations). In all cases the seeds were pre-soaked for 24 hours. (a) Average germination time, in days, between the first and last appearance of individuals for all species and water levels, as far as available. The number on top of the bars represents the number of sprouted seeds that are averaged in the bar (holds for part (b) as well). Note that germination times beyond a few days excessively increase experiment duration. (b) Average stem length of germinated individuals after 15 days. [Colour figure can be viewed at wileyonlinelibrary.com]



**Figure 6.** Maximum plant length plotted against seed size under typical laboratory conditions and in the absence of nutrients in the sand. The circles are the species we selected for further analyses. Some species plotted here were tested only once for selection purposes and are not listed in Table II as follows: AP, *Alisma plantago-aquatica*; CP, *Carex pseudocyperus*; PM, *Persicaria maculata*; RSL, *Raphanus sativus Longipinnatus*; Sg, *Sorghum bicolor* (other batch than in Tables II, III). [Colour figure can be viewed at wileyonlinelibrary.com]

Transport mode of seeds in experimental flows

The Rouse number was calculated for 0.0075 m/m slope and 0.03 m channel depth. The settling velocities and seed diameters of the species ranged over an order of magnitude and this resulted in concurrent differences in particle Reynolds

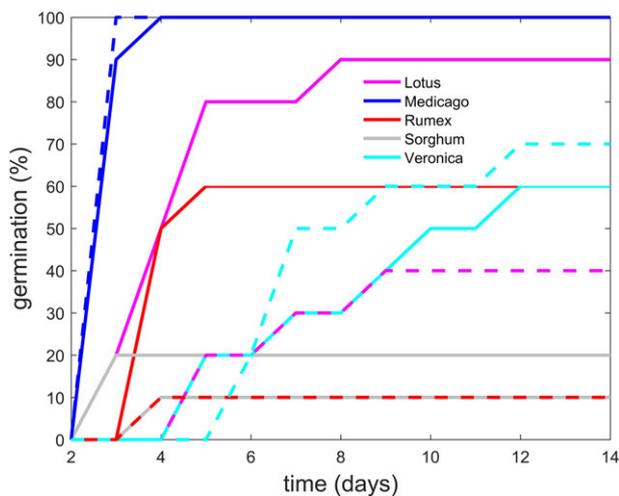
**Table III.** Properties determining seed transport by water. Seed diameter  $D_s$  and settling velocity  $w_s$  were measured experimentally. The Rouse number was calculated for 0.0075 m/m slope and 0.03 m channel depth

Species	$D_s$ (mm)	$w_s$ (m/s)	$Re_p$	Z
<i>Lotus pedunculatus</i>	1	0.066	66	3.5
<i>Medicago sativa</i>	2.5	0.058	146	3.1
<i>Rumex hydrolapathum</i>	3.0	0.037	112	1.8
<i>Sorghum bicolor</i>	5	0.12	614	6.5
<i>Veronica beccabunga</i>	0.3	0.01	2.9	0.5

and Rouse numbers (Table III). The Rouse number was largest for *Sorghum bicolor*, followed by *Lotus pedunculatus* and *Medicago sativa* (Table III). These three seed types were likely transported as bedload, under the described experimental conditions. *Rumex hydrolapathum* was intermediate between bedload and suspended load for the given flow conditions, and the transport mode of *Veronica beccabunga* was transported as washload or in suspension, depending on the experimental conditions.

Sensitivity to water depth in the sprouting phase

When the growth experiments were repeated for the five selected species under controlled laboratory lighting, temperature and antipest conditions, all species sprouted after 4–5 days except for *Medicago sativa*, which sprouted after only 2 days (Figure 7). *Veronica beccabunga*, *Sorghum bicolor* and *Lotus pedunculatus* sprouted slightly faster when the water was at



**Figure 7.** Fraction of germinated seeds for five selected species. Dashed lines indicate seeding at 10 mm above the water surface; solid lines indicate seeding at the water surface. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the soil surface than for the lower water level, while *Medicago sativa* and *Rumex hydrolapathum* sprouted equally quickly (Figure 7). Although these measurements were conducted for only 10 seeds, the results generally agreed with earlier pilot experiments.

After several days the plants reached their maximum shoot height, except for *Sorghum bicolor*, (Figure 8). Plant growth was approximately logistic, with an initial acceleration and an asymptotic decrease as plants reached their maximum length. The five species had considerably different root and shoot

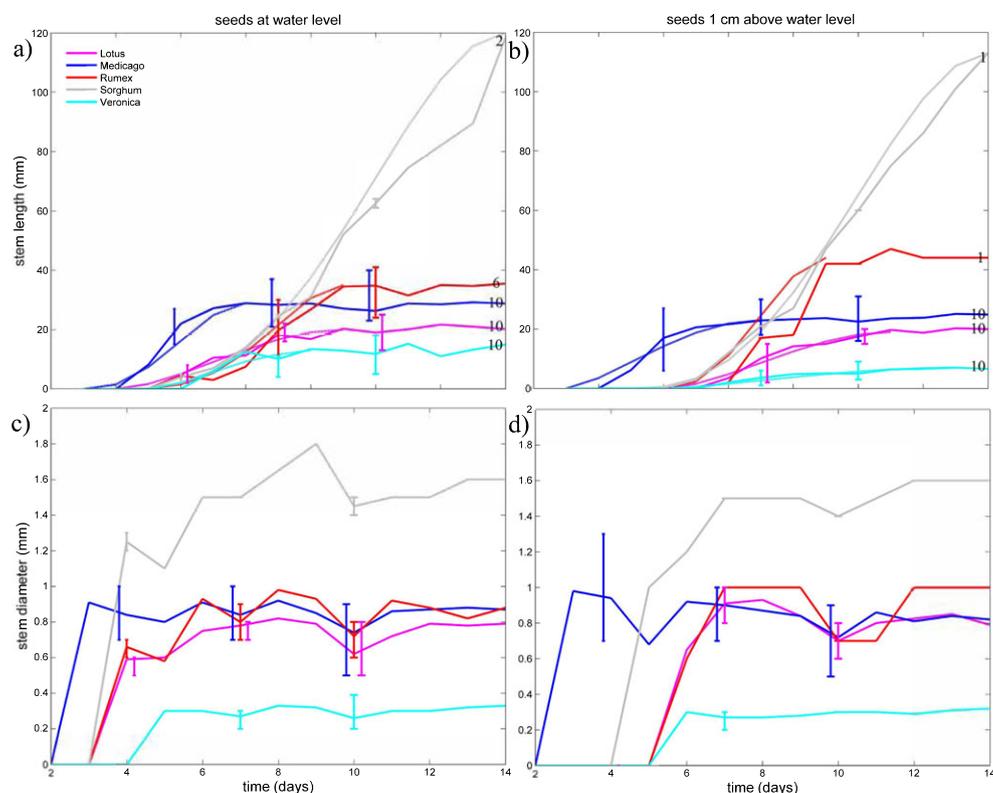
lengths after 2 weeks of growth. Water level, however, had a minor effect on plant growth (Figure 9). Root and shoot diameters were fairly similar for *Medicago*, *Rumex* and *Lotus*, whereas *Veronica* was thinner and *Sorghum* was thicker.

### Increase in flow resistance by seedling stems

The flow resistance of *Rumex hydrolapathum* was largest, with about 50% reduction in flow velocity relative to the bare sand bed (Figure 10), with *Medicago sativa* a close second. *Veronica beccabunga* and *Lotus pedunculatus* had a somewhat smaller flow resistance (Figure 10a). There was, however, an effect of the fraction of germinated seeds, which was most clear for *Sorghum bicolor*, which showed the lowest reduction in flow velocity. Given the constant discharge and slope, a reduction in flow velocity was compensated for by an increase in water depth (Figure 10b). We compared our measured Chezy value (derived through Equation (8)) with the predicted values according to Equation (5). The reduction in flow velocities was similar to what was expected based on the Baptist equation (Equation (5)) (Baptist *et al.*, 2007), when we assumed a drag coefficient of 2, which is a reasonable assumption for the stem Reynolds number of 150 in our experiments with cylindrical stems (Figure 10c). An increase in roughness increase by a factor 2–4 was found for the different vegetation species.

### Reduction of bank erodibility by rooting

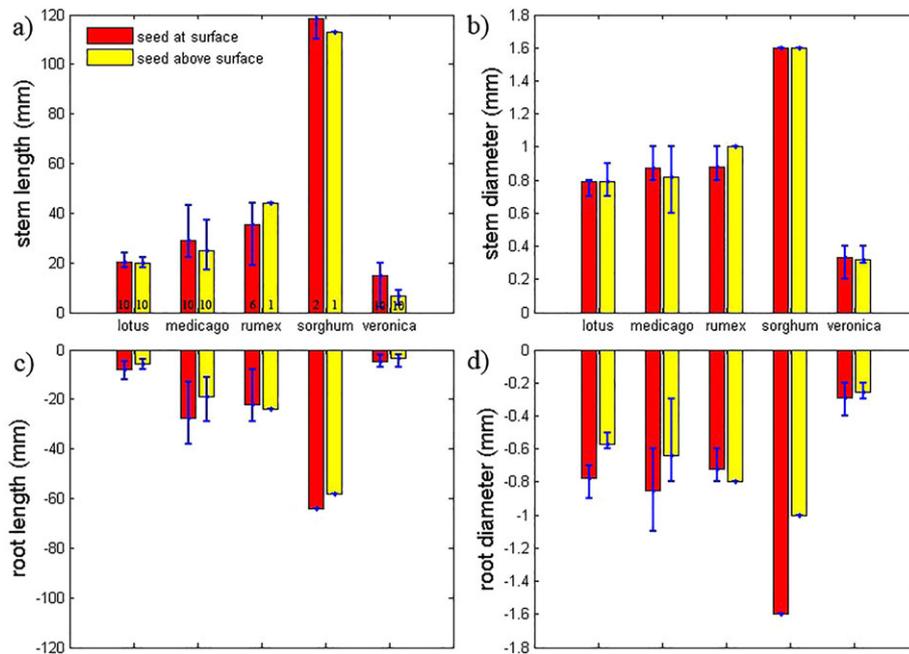
Rooting effects on bank erosion rates differed between the species (Figure 11). All vegetation types reduced bank erosion considerably, relative to the control experiment without plants.



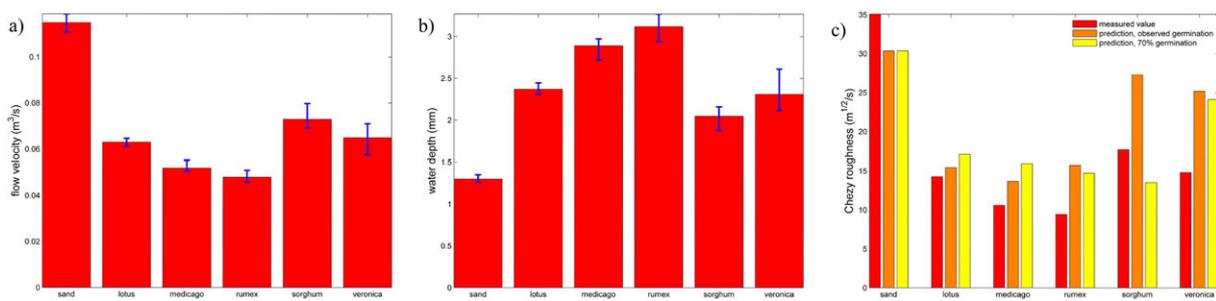
**Figure 8.** Average growth curves for the five selected species on the sand bed at the water surface (a,c) and on the sand bed at 10 mm above the water surface (b,d) for seedling length (a,b) and stem diameter (c,d). Measurements were conducted on the germinated individuals of 10 seeds per species per condition, so that fluctuations in dimensions indicate variability rather than temporal change. The dashed lines are fitted growth curves based on Equation (4) (Yin *et al.*, 2003) (Table IV). The numbers in parts (a) and (b) indicate the number of sprouted seeds. Minimum and maximum values are displayed after 4, 7 and 10 days. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**Table IV.** Coefficients obtained by fitting the growth equation (Equation (4)) to time-dependent size data of five selected vegetation species

Species	Seeds at water level			Seeds 10 mm above water level		
	Max. length (mm)	$t_e$ (days)	$t_m$ (days)	Max. length (mm)	$t_e$ (days)	$t_m$ (days)
<i>Lotus pedunculatus</i>	20	7	3	19	7	3
<i>Medicago sativa</i>	29	5	3	23	6	2
<i>Rumex hydrolapathum</i>	35	7	5	44	5	3
<i>Sorghum bicolor</i>	120	12	8	113	11	7
<i>Veronica beccabunga</i>	13	5	2	7	9	3



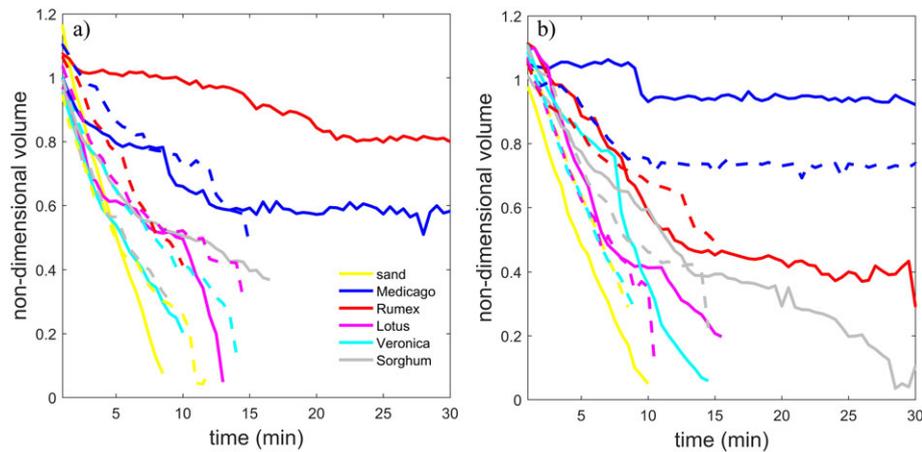
**Figure 9.** Shoot and root lengths measured after 14 days, at the end of the growth period: (a) shoot lengths; (b) shoot diameters; (c) root lengths; (d) root diameters. ‘Seed at surface’ means that the water level is equal to the bed level with seeds, and ‘seed above surface’ means that the bed level is 10 mm above the water level. The numbers in the bars of plot (a) are the number of sprouted plants used. [Colour figure can be viewed at wileyonlinelibrary.com]



**Figure 10.** Measured flow velocity and derived vegetation resistance measured in shallow flow by dye tracer for a seeding density of 2 seeds/cm<sup>2</sup> after 7 days. (a) the flow velocity based on the breakthrough time of the tracer front; (b) the corresponding water depth based on continuity of imposed discharge and measured velocity; and (c) the Chezy value based on measurements (Equation (8)) and predictions (Equation (5)). [Colour figure can be viewed at wileyonlinelibrary.com]

The effect of *Medicago* was much greater than that of *Veronica* or *Lotus*, especially after 9 days when the bank could not be eroded by the imposed flow. This was at least partly due to the root lengths of the species (Figure 9c). The roots of some species also reduced bank erosion to zero at a certain channel width, in contrast to weaker species and the control experiments. The control runs with sand only showed a linear decrease in volume over time. This indicates that shear stress is

not limiting potential bank erosion as all experiments had the same flow conditions; rather, the binding effects of roots and the protective shielding of exposed roots together gradually reduced erodibility of the bank. Although there was considerable variation between duplicates and between 7 and 9 days of growth before subjecting the samples to flow, most species showed either a constant or increasing resistance to erosion by the flow due to further growth of the roots, as observable



**Figure 11.** The part of the sediment block that remains, over time, in the Friedkin experiments based on detection of the bank line and assuming a constant height. (a) All species when they are still developing after 7 days and (b) when all species except sorghum have reached their final dimensions after 9 days. Species were seeded on sand 10 mm above the water surface. The dashed and solid lines are duplicates to obtain a feeling for variability. Note that not all lines start at the same height, which is due to initial collapse to angle of repose of the 90° bank slope after wetting, which is observed as a bank line change. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

in the constant or increasing time before the sediment was reduced by, say 40%. At this point, the channel had on average widened by almost a factor of two and the bed shear stress reduced by a similar factor.

## Discussion

To summarize, we examined four vegetation species with potentially different eco-engineering effects in morphological experiments from the frequently used *Medicago sativa*, which extends previous work by Clarke (2014). The four species, *Lotus pedunculatus*, *Rumex hydrolapathum*, *Sorghum bicolor* and *Veronica beccabunga*, grow best under different inundation conditions and have different eco-engineering effects. Nevertheless, all four grow fast under laboratory conditions, with a development timescale of 5 days or less, which makes them practically usable and suitable for morphological experiments (Kleinhans *et al.*, 2015). As with *Medicago sativa*, all four species have their maximum growth rate around day 3 and their final length after 7 days, except *Sorghum bicolor*, which has its maximum growth rate after 7 days and its maximum length after 12 days. The lengths of the species range from 10 to 40 mm, with outlier *Sorghum bicolor* up to 120 mm. Assuming typical water depths of 5–30 mm in the channels, these four species will be emergent except in the channels.

Both the sensitivity to water depth and the duration of growth allow for control on where species establish in experiments. The magnitude and timing of flow events following establishment will affect which species survive, dependent on age and water depth.

Based on the measured Rouse and particle Reynolds numbers we derived for typical experimental conditions, we infer for landscape experiment conditions that *Sorghum bicolor*, *Medicago sativa* and *Lotus pedunculatus* are transported as bedload in typical fluvial and tidal landscape experiments, and possibly in suspension on steeper and more dynamic alluvial fans and fan deltas. *Veronica beccabunga* seeds, on the other hand, are transported as washload, and *Rumex hydrolapathum* is transitional between bedload and suspended load. This implies that *Medicago sativa*, *Sorghum bicolor* and *Lotus pedunculatus* seeds may get transported into local lows. *Rumex hydrolapathum* is partly transported as suspended load, which means that it will reach higher elevations in the water column, and *Veronica beccabunga* is transported as washload

or in suspension, meaning that it can be transported onto bars and banks in very shallow and slow flows, possibly in between other vegetation. These differences can therefore result in a sorting of the vegetation with *Rumex hydrolapathum* and *Veronica beccabunga* ending up on higher bed elevations than *Medicago sativa*, *Lotus pedunculatus* and *Sorghum bicolor*. In different experimental settings species might reach higher or lower elevations as shear stress increases or decreases respectively, and these inferences do not include competition for space effects. The species are sufficiently different in their sensitivity to inundation to be able to select different behaviours; for example, *Lotus pedunculatus* and *Medicago sativa* are able to sprout under water whereas the others are not. Three species that show a clear difference in germination rate for different water availability, namely *Lotus pedunculatus* and *Rumex hydrolapathum*, which sprout best under wet conditions, and *Sorghum bicolor*, which sprouts best under dry conditions.

Important eco-engineering effects are flow retardation through hydraulic resistance, reducing forces on the plants and increasing survival for new plants, and bank strength due to rooting, increasing the chances of survival on the banks. All vegetation species significantly retard the flow, with the highest reduction due to *Rumex hydrolapathum* and the smallest due to *Sorghum bicolor* for a constant seeding density. For emergent vegetation with equal drag coefficients, the only two changing variables are the stem density (the number of stems per square meter) and the stem diameter. As we seeded the same vegetation density, differences in flow retardation should result from differences in stem diameter and germination rate between species. An increase in flow retardation with increasing stem diameter was present in most of our results. *Lotus pedunculatus*, *Rumex hydrolapathum* and *Medicago sativa* retarded the flow to an expected degree based on only their stem diameter, whereas *Sorghum bicolor* retarded the flow to a smaller degree because of its limited germination rate. Part of the flow retardation in the experiments with *Sorghum bicolor*, however, comes from the unspouted seeds in the flume. *Veronica beccabunga*, on the other hand, retarded the flow substantially more than expected, as it developed some dense clumps despite the attempts to seed as uniformly as possible (Figure 10). The degree to which these eco-engineering effects change in the presence of fine sediment remains to be tested. Possibly the flow retardation leads to enhanced sedimentation of fine sediments and low-density sediments. Furthermore, interactions and possible facilitation between multiple species

**Table V.** Suggested species usage in landscape experiments. Added flow resistance is expressed as the multiplication factor of the bare bed resistance. Erosion reduction is expressed as the approximate multiplication factor on the bank erosion in the bare control Friedkin experiment

Species	Vegetation type	Natural habitat	Added flow resistance	Erosion reduction
<i>Lotus pedunculatus</i>	Saltmarsh	Lower intertidal area	2.5	1.5
	Grasses	Floodplain		
<i>Medicago sativa</i>	Mangrove trees	Lower intertidal area	3	>5
		Channels		
<i>Rumex hydrolapathum</i>	Riparian trees	Floodplain	3	3
	Mangrove trees	Intertidal area		
<i>Sorghum bicolor</i>	Larger trees	Floodplain	2	2
<i>Veronica beccabunga</i>	Saltmarsh	(Higher) intertidal area	2	1.3
	Riparian grasses	Floodplain, waterline		

in one experiment offer exciting prospects for control in more complex landscapes.

Experimental studies of biogeomorphological interactions tend to focus on the bank strength added by vegetation (Tal and Paola, 2007; Braudrick *et al.*, 2009). In rivers the main effect of trees may indeed be to increase the strength of banks (Smith, 1976; Millar, 2000; Tal and Paola, 2007; Murray *et al.*, 2008; Gurnell *et al.*, 2012), but in some river types (Kleinhans *et al.*, 2018) and in other ecotopes flow retardation or other effects could be more important (Bouma *et al.*, 2007; Corenblit *et al.*, 2011; Nepf, 2012b; Schwarz *et al.*, 2014). We found that *Veronica beccabunga* and *Lotus pedunculatus* can reduce erosion by 30–50%, whereas *Sorghum bicolor*, *Medicago sativa* and *Rumex hydrolapathum* reduce erosion up to a factor of four, which is due to differences in root length (Perona *et al.*, 2012). The same differences in root length also increase plant resistance against uprooting (Edmaier *et al.*, 2014), which is also observed in natural riparian systems (Corenblit *et al.*, 2011; Gurnell *et al.*, 2012). However, this strongly depends on water depth and bank height (Perona *et al.*, 2012), so that these findings need testing and calibration for different experimental scales, conditions and setups, including the conditions affecting plant growth and survival. Nevertheless, the trends and differences between species are likely robust for many fluvial and tidal landscape experiments.

The above leads to a tentative designation of the five species to different purposes (Table V). Owing to their large effect on bank erosion, *Rumex hydrolapathum* and *Medicago sativa* behave similarly to riparian and mangrove tree species in small-scale experiments. In nature, flow retardation due to fully grown trees is relatively minor compared to marsh species, because of the large distances between tree trunks, while riparian trees in the bushy life stage provide a high flow resistance (van Oorschot *et al.*, 2016). The latter is represented well by these two species following hydrochorous seed distribution. *Rumex hydrolapathum* may represent riparian tree species particularly well as its seeds are partly transported in suspension and therefore end up on higher elevations in the system. On the other hand, *Medicago sativa* sprouts particularly well under moist conditions, which makes this species perhaps suitable to represent mangrove vegetation in intertidal habitats, for which there are currently no landscape experiments available. *Medicago sativa* may, however, cause problems in landscape experiments with shallow water depths, because it tends to develop close to the waterline or even under water due to its spreading characteristics, which is unwanted when simulating riparian trees that develop at higher bed levels. However, this may possibly be used to represent reed marsh or mangrove development with organic matter accumulation, or, depending on the force of the floods, tree species that have ample dead wood. The flow retardation by *Lotus pedunculatus* and *Veronica beccabunga* is smaller when seeding densities are similar, but preliminary

testing in landscape experiments suggests that these species tend to settle at much higher plant densities. In nature the number of stems of grass-like species is obviously much larger than that of tree-like species, even in the seedling life stage, and this is well represented by the settling and growth patterns of these species. Therefore, *Veronica beccabunga* and *Lotus pedunculatus* significantly retard the flow and would likely capture sediment, while their effect on bank erosion is limited. This makes them suitable to represent marsh or freshwater floodplain species. It is, however, important to take into account that *Veronica beccabunga* can occupy higher areas, while *Lotus pedunculatus* will occur close to the channels when spread hydrochorously. This makes them suitable for different types of experiments. *Sorghum bicolor* can best represent large trees or even larger forested areas as its roots can stabilize the sediment significantly. It sprouts poorly under moist conditions, however, so it is best seeded by hand and left to germinate with little water.

The differences between these species lead to development of landscapes through eco-engineering effects and hydromorphological feedbacks. *Veronica beccabunga* and *Lotus pedunculatus* might colonize the relatively wet areas in experiments where they drive sedimentation due to flow retardation, therefore reducing the flow shear stress and inundation pressure. Sedimentation might also facilitate the development of other species such as *Sorghum bicolor* and *Rumex hydrolapathum* and therefore drive a process similar to natural succession. These two species might then further bind the sediment due to their relatively large and strong roots with, for example, a fixed bar as a result. Because these are living vegetation species they can be used in fluvial and tidal landscape experiments, as the processes (e.g. binding sediment and retarding flow velocity) by which they affect morphodynamics are similar in these different settings – for example, experiments with respect to tidal channel formation (e.g. Stefanon *et al.*, 2010; Vlaswinkel and Cantelli, 2011), meandering rivers (e.g. Tal and Paola, 2010) or vegetated deltas (e.g. Piliouras *et al.*, 2017).

All the above suggestions need to be tested further under specific application conditions. Our set of tests provides a comprehensive and fast forecast of plant settling conditions, experimental duration and eco-engineering effects that reduce pilot testing time and quantify effects that are difficult to isolate in costly, large and complex living landscape experiments.

## Conclusions

Seedlings of five vegetation species were tested for use in biogeomorphological landscape experiments and found to have practically usable sprouting times, different sensitivity to hydrodynamic conditions and different eco-engineering

effects. In the absence of nutrients in the sand, growth ceases at a sprout size depending on seed size. We interpreted their possible representations in the context of certain landscape experiments, but these depend on the scale and purpose of experiments.

For landscape experiments with bars and channels, *Rumex hydrolapathum* and *Medicago sativa* can be used to represent (young) trees, while *Lotus pedunculatus* and *Veronica beccabunga* can represent reed/grass-like vegetation, for example on marshes. The effect on bank erosion of *Rumex hydrolapathum* and *Medicago sativa* is substantially larger than that of *Veronica beccabunga* and *Lotus pedunculatus*, but their effects on flow velocity are similar. When spread hydrochorously *Veronica beccabunga* and *Rumex hydrolapathum* will colonize the higher elevations because their seeds are (partly) transported in suspension. *Sorghum bicolor* can best represent riparian trees as it grows solitarily and its roots can add significant bank strength, while its effect on flow velocity is limited. However, *Sorghum bicolor* sprouts poorly under moist conditions.

Generic experimental methods were used for characterization of seedling properties, these being growth speed, seed behaviour in suspension, sensitivity to water depth in sprouting, and flow resistance and bank erodibility as functions of seeding density. The discussed species provide a benchmark to choose from in physical modelling, and the methods and approaches can be used for other species as well as at other length scales and timescales of future experiments.

**ACKNOWLEDGEMENTS**—Discussion with three anonymous reviewers and guidance from the guest Editor are gratefully acknowledged. This research was funded by the European Research Council (ERC Consolidator agreement 647570) to PI Kleinhans. Part of this work was conducted as a BSc thesis project by SdL. Support and discussion by Chris Roosendaal, Arjan van Eijk, Mijke van Oorschot and Lonneke Roelofs are cordially acknowledged. The authors contributed in the following proportions to conception and design, data collection, analysis and conclusions, and manuscript preparation: IRL (30, 60, 40, 60%), SdL (10, 30, 20, 10%), GvB (20, 10, 0, 0%), SS (10, 0, 10, 10%) and MGK (30, 0, 30, 20%).

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