SEED-SEDIMENT DYNAMICS: INSIGHTS FROM EXPERIMENTS ON THE BEHAVIOUR OF SEAGRASS SEEDS IN SAND MIXTURES TO INFORM SEAGRASS RESTORATION SCALE-UP METHODS

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SUMMARY

Seagrass meadows are vital coastal ecosystems, yet their global decline has prompted the need for scalable restoration strategies. Traditional seed-based restoration methods remain limited by low germination rates, labor-intensive deployment, and poor scalability. This study explores a novel, multidisciplinary approach that integrates ecological restoration with hydraulic engineering by investigating the dynamics of seagrass seed behavior in sand-water mixtures. A series of controlled physical laboratory experiments, were conducted to analyze the settling behavior and final burial depth of *Zostera marina* seeds and seed mimics in sediment slurries of varying grain sizes and concentrations. Results reveal that hindered settling and particle segregation significantly influence seed distribution, with medium-coarse sand at low concentrations (5–10%) yielding optimal burial depths (1–5.5 cm) for germination and protection. The findings highlight the importance of fluid-particle interactions in restoration design and demonstrate the potential of hydraulic sediment placement as a scalable method for seagrass restoration. This work bridges marine ecology and dredging engineering, offering practical insights for field applications and large-scale ecosystem recovery.

INTRODUCTION

Seagrasses are vital to coastal ecosystems, offering sediment stabilization, carbon storage, and habitat for marine life (Duarte & Krause-Jensen, 2017; Infantes et al., 2022). Despite their ecological significance, seagrass meadows have declined sharply, with around one-third of European areas lost (Waycott et al., 2009; de Los Santos et al., 2019). This degradation disrupts the positive feedback mechanisms, such as sediment stabilization and water clarity (van der Heide et al., 2011). Once these feedbacks are broken, natural recovery becomes difficult, raising the need for active restoration interventions.

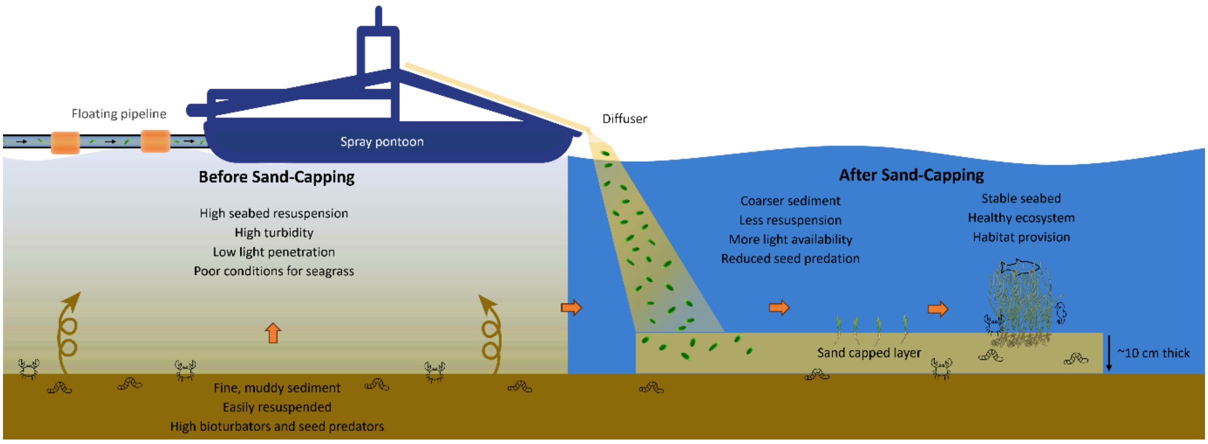

Figure 1: Visualisation of the effects of sand capping technique

Zostera marina, known for its high seed yield and broad distribution, is a strong candidate for seed-based restoration (Kilminster et al., 2015; Marion & Orth, 2008; Short et al., 2007). Yet, conventional methods face scalability issues due face scalability issues due to low germination rates, labour intensity, and diver safety concerns (Bayraktarov et al., 2016; van Katwijk et al., 2016). To address these challenges, this study explores a novel approach that integrates seed-based restoration with sand-capping. A sediment management technique commonly used in dredging operations for contaminated soils. By placing a thin layer of coarser sediment over in this case finer, organic-rich substrates it reduces resuspension and improves light penetration. Recent studies have demonstrated its potential to enhance seagrass habitat conditions by stabilizing sediments and increasing erosion thresholds (Flindt et al., 2022; Oncken et al., 2022).

The success of this integrated method hinges on seed burial depth within the sediment cap, as germination rates are highest between 2–4 cm, where seeds are protected from erosion and predation (Infantes et al., 2016; Jarvis & Moore, 2015; Jørgensen et al., 2019). Achieving this at scale requires understanding seed behaviour in sediment-water mixtures, both at particle and operational levels.

EXPERIMENT TERMINAL SETTLING VELOCITY

To investigate seed behaviour in sediment-water mixtures, two experimental phases were conducted. The first focused on measuring the terminal settling velocity of *Zostera marina* seeds, as this has previously only been assessed from a biological perspective. Seeds were released into a graduated cylinder filled with saline water to prevent germination and be comparable to natural environments. A LED screen provided uniform backlighting for trajectory tracking using a GoPro camera. Individual seeds from various European populations were measured along three axes to assess correlations with shape, size, and density and released into the cylinder (32 ppt, 400 mm height). The seeds were tracked using high-resolution video analysis. No clear correlation between shape, density, or settling velocity was found, although the variability aligns with literature. A multi-step video analysis workflow was applied, including cropping, grayscale conversion, and distortion correction. The Trackpy package (Kim et al., 2018) was used to track individual trajectories. The average settling velocity was 5.97 cm/s (SD = 1.51 cm/s, CV = 0.252).

Due to limited availability of *Zostera marina* seeds, various land-based seed mimics were tested to replicate natural variability. Unlike tested synthetic particles, these biological proxies are affordable and accessible, as seagrass seeds must be hand-collected from donor meadows. Clover seeds, with a similar elliptical shape and settling velocity (6.32 cm/s), were identified as the most suitable proxy for subtidal *Z. marina*. Subtidal seeds generally settled faster than intertidal ones, reflecting biotope differences. In previous research seagrass seeds with settling velocities ≥ 5.5 cm/s are considered viable for restoration (Meysick et al., 2019; Lowell et al., 2021; Marion et al., 2003).

EXPERIMENT SEED DISTRIBUTION

Various sediment concentrations (0.05, 0.1, 0.15, 0.2, 0.3) were used to investigate seed distribution using mono-disperse sand types—coarse, medium-coarse, and fine. Medium-coarse sand (d_{50} = 0.35 mm) was selected for its comparable settling velocity to the seeds, while fine (d_{50} = 0.20 mm) and coarse (d_{50} = 0.43 mm) sands assessed relative velocity effects. Experiments were conducted in a 120 cm tall, 10.5 cm diameter acrylate pipe, equipped with a custom 3D-printed plug, gate valve, and drainage system. Phase II included an extension pipe to create a still water column.

Each test used approximately 100 seed mimics. In Phase I, sediment was added to achieve the desired concentration, followed by saline water (32 ppt) and the mimics. The column was manually mixed and allowed to settle. The sediment layer was pushed upward and sliced in 1 cm increments to count the number of seeds per layer after being drained. In Phase II, the sediment-seed mixture was prepared above a still water column and mixed using a stirrer attached to a power tool. The mixture was released by opening the valve, with a printed mesh installed to reduce horizontal flow. The settled layer was analysed using the same slicing method.

Contrary to the hypothesis of homogeneous distribution, clear segregation occurred, especially at higher concentrations, with seeds accumulating near the surface. Phase I showed stronger segregation due to turbulence, while Phase II yielded better results. Medium-coarse sand at 0.05–0.1 concentrations buried most seeds within the survival layer between 1–5.5 cm depth. Fine sand showed similar trends, though segregation increased above 0.2. Coarse sand consistently led to surface accumulation.

Video analysis revealed that seeds behaved differently from sand particles, exhibiting rotational and hovering motions influenced by turbulence and return currents. These dynamics contributed to segregation and must be considered in future restoration designs.

DISCUSSION

Understanding the settling behaviour of seagrass seeds is essential for designing effective restoration techniques. This study revealed substantial variability in seed size and density, resulting in a wide range of settling velocities. While proxy seeds were necessary due to limited availability of *Zostera marina*, their use introduced subtle differences in settling paths as seen in the video analysis, such as increased horizontal drift and rotational movement, which must be interpreted with caution.

Although sediment types were selected to match seed settling velocities, segregation effects were still observed—particularly at higher concentrations. This is attributed to the seeds' larger size and lower density relative to the sediment, which alters their interaction with the surrounding fluid. In dense mixtures, the reduced density contrast can even cause seeds to rise rather than settle. Their ellipsoidal shape and sensitivity to flow variations further complicate their behaviour, making them more prone to chaotic motion.

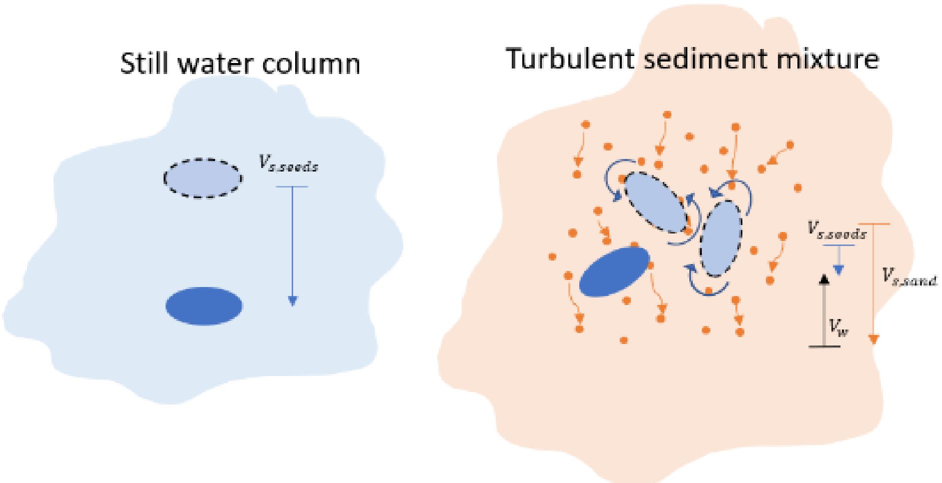

Figure 2: Visualization of differences in seeds settling response

Phase I captured hindered settling effectively but was influenced by turbulence and wall effects. Phase II, simulating slurry injection in a confined manner, produced more realistic results but was still affected by factors like entrainment and release height. This highlighted the need for further refinement of experimental setups and sediment grading to better replicate field conditions and improve predictive accuracy for large-scale restoration applications.

These findings were used in subsequent research in larger scale research and field tests aiming to restore an area in Scotland with previous presence of seagrass but degraded due to site conditions. Previous restoration without sandcapping in this area was unsuccessful. Initial results showed a successful sand cap of 10cm with seeds distributed in the viable layers due to initial germination success.

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