Ex-situ mariculture can support the restoration of the endangered seagrass *Zostera capensis*

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Seagrass meadows face ongoing declines and are increasingly targeted for restoration. Traditional in-situ restoration techniques involve trade-offs between restoration success and donor meadow impacts. To overcome these challenges, we provide the first assessment of ex-situ mariculture of the endangered seagrass *Zostera capensis* to support its restoration in South Africa. Seagrass cores with diameters of 5 cm and 10 cm, including their sediment, were harvested and grown in mariculture pools for 195 days. Changes in seagrass leaf length (cm) and shoot density (cm^2) were monitored and the effect of core size on these morphometrics was investigated. Core size had a significant effect on seagrass shoot density and leaf length, as smaller cores had lower shoot densities and leaf lengths over time, suggesting that larger cores might be more effective to maximise seagrass cover during ex-situ mariculture. Overall, shoot densities saw limited increases for the first nine days, followed by a large percentage increase between days 9 and 24, before growth remained steady until peak shoot density was reached between days 100 and 124. Leaf lengths gradually increased until peaking between days 100 and 124. This study successfully demonstrates the proof of concept that ex-situ mariculture can sustainably upscale *Z. capensis* restoration by increasing the amount of plant material available for re-transplantation. To build on the work presented here, we provide a framework, incorporating guidance from published literature, to advise future seagrass restoration trials.

Significance:

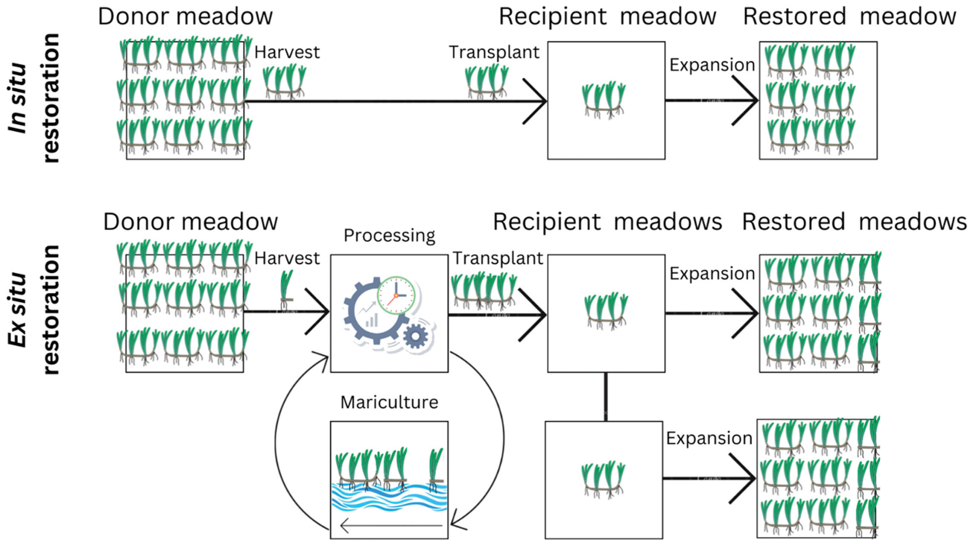
Seagrass restoration often involves trade-offs between the volume of seagrass harvested for translocation, restoration success and impacts on donor sites. Ex-situ mariculture reduces disturbance to donor sites and increases restoration scalability by increasing transplantable seagrass biomass beyond that which was initially collected. The first successful proof of this concept for the endangered *Zostera capensis* is presented to illustrate how seagrass mariculture will prove to be an important tool for maintaining seagrass meadows into the future.

Introduction

Globally, seagrass populations are declining due to cumulative anthropogenic pressures, resulting in an estimated loss of ~19% of their global extent.[1] Concerningly, population loss and habitat disturbance reduce seagrass ecosystem service provision.[2] As such, management strategies aimed at restoring seagrass meadows are urgently needed[3], with effective in-situ restoration, via transplantation, shown to be possible[4]. For example, the largest seagrass restoration project was completed in Virginia, USA, where 7 km^2 of *Zostera marina* meadows were restored.[5] Advances in seagrass restoration may support seagrass ecosystem service provision, with Lange et al.[6] suggesting that restored *Z. marina* meadows are capable of storing ~33 g C/m^2 per year post-restoration, whilst McSkimming et al.[7] found that faunal richness and abundance of restored *Amphibolis antarctica* meadows was comparable to that of healthy natural meadows one year post-transplantation.

Unlike rehabilitation, which refers to the natural recolonisation and establishment of seagrass meadows, restoration has been defined by Tan et al.[4] as active intervention aimed at returning degraded habitats to a state which resembles the natural condition, and often involves the physical planting of seagrasses and/or their seeds. In this study, the term seagrass restoration was used to encompass the physical growth and re-planting of seagrass material into habitats from which seagrasses had been lost. Despite the successful implementation of in-situ seagrass restoration projects (see, for example, Lange et al.[6] and Watson et al.[8]), some projects require large amounts of seagrass biomass to be harvested, which can damage donor meadows and, in the case of unsuccessful transplantation, negatively impact overall seagrass cover.[9] As such, there is a trade-off between the amount of seagrass harvested for transplantation, restoration success and the impact on donor sites.[10]

Ex-situ seagrass mariculture provides an ecologically sustainable means to optimise and upscale seagrass restoration by increasing the amount of plant material available for transplantation through the growth of seagrass in aquarium facilities[10], which minimises disturbance to donor sites by reducing the amount of donor material collected (Figure 1). Previous ex-situ seagrass growth experiments have predominantly focused on germinating new plants from seeds or cuttings, whilst using increased leaf length (cm) and relative shoot density to characterise successful growth.[11-13] Monitoring changes in leaf length and shoot density is important, as these growth metrics can serve as an indication of the future ecosystem service provisioning capacity of seagrass post transplantation. For example, increased canopy complexity (leaf length and shoot density) can reduce hydrodynamic energy, thus minimising sediment resuspension, improving water filtration and forming muddy carbon-capturing soils.[14] Despite studies providing evidence for the successful ex-situ propagation and growth of some seagrass species from seeds, such as *Enhalus acoroides*[11] and *Posidonia australis*[12], this method is not feasible for species lacking an abundant and consistent supply of seeds. As such, the ex-situ mariculture of such species, including *Zostera capensis*, will rely on the cultivation of harvested plant material from in-situ seagrass meadows. Thus far, to our knowledge,



Source: Adapted from van Katwijk et al.[10]. © Katwijk et al., 2021[10] (reproduced under a CC BY 4.0 licence).

Figure 1: Ex-situ mariculture, in comparison to in-situ translocation, allows for the sustainable upscaling of seagrass restoration by increasing the amount of plant material available for transplantation, whilst minimising damage to the donor.

ex-situ mariculture of wild harvested seagrass has only been employed for *Z. marina*[15], and it remains unclear whether it is a viable strategy for seagrasses elsewhere globally.

In southern Africa, anthropogenic stressors have led to localised extinctions of the endangered Cape dwarf-eelgrass, *Z. capensis.*[16,17] Further, a population loss of 33% (~742 ha) in South Africa[16,18] highlights the need for interventions through restoration to reverse population declines and preserve seagrass ecosystem services.[15] Seagrass restoration in southern Africa has little evidence and support, with only three recent studies, with variable outcomes.[8,9,19] Transplantation of three different core sizes in two South African estuaries by Mokumo et al.[9] resulted in failed transplantation efforts, due to flooding and likely sedimentation of transplantation sites during winter, with no transplants surviving after 12 weeks. In contrast, Amone-Mabuto et al.[19] in Maputo Bay, Mozambique and Watson et al.[8] in Langebaan Lagoon, South Africa showed survival and spread of transplanted cores over 18 months. Interestingly, *Z. capensis* has rarely been observed with seeds, and it is likely that this seagrass strongly relies on asexual reproduction.[16,20,21]

In this article, we present the first attempt of ex-situ seagrass mariculture for *Z. capensis* globally, by testing the potential for using mariculture as a means to upscale and optimise *Z. capensis* restoration practices, via ex-situ growth of donor seagrass material. Beyond testing a basic proof of concept, we also assessed the effect of core size on seagrass shoot density and leaf length change over time. We hypothesised that seagrass cores would increase in shoot density and leaf length over time, and, because Amone-Mabuto et al.[19] found that larger cores exhibited increased survival rates, we expected larger cores to have higher shoot densities and leaf lengths. Finally, we used the results of this study and those of previous restoration trials, both in South Africa and elsewhere internationally, to develop a framework that can guide future seagrass mariculture efforts globally.

Methods

Seagrass collection study site

Seagrass plants were collected from monospecific intertidal meadows of *Z. capensis* at Langebaan Lagoon (33°08'42.3"S, 18°03'43.0"E; Figure 2), situated in the cool-temperate bioregion along the South African west coast.[16] Langebaan Lagoon is an important conservation area in the West Coast National Park, recognised nationally and internationally as a Marine Protected Area and Ramsar Site[22,23], supporting one of the largest seagrass populations in South Africa (~335 ha[24]). *Zostera capensis* cover has declined across the lagoon, with a prolonged loss of ~38% between 1960 and 2009.[25] Declines are likely linked with the construction of the adjoining Saldanha Bay Harbour[26], including the associated dredging practices, which altered the hydrodynamics of the lagoon and increased the sediment load in the water column[27]. At local scales, habitat disturbance from bait harvesting and trampling, particularly from kite surfing, are the main drivers of seagrass loss.[25]

Harvesting donor seagrass material

Intertidal seagrass cores were collected from Centre Banks (Figure 2), as this site has a relatively stable and expansive area of seagrass which has experienced minimal fluctuations in population size over the last 8 years.[24] Cores were randomly harvested at 5 m intervals during low tide, using two polyvinyl chloride (PVC) corers (Supplementary figure 1a) of 5 cm and 10 cm diameters, each to a depth of 10 cm, with 24 samples per core size collected ($n = 48$ cores in total). Cores were placed into plastic pots lined with 100% cotton cloth, which were then placed into plastic planting containers (20 cm x 15 cm x 10 cm) and filled with unvegetated sediment from the donor site (Supplementary figure 1b). All pots and sediment-filled containers were transported to the mariculture facility at Stellenbosch University (Supplementary figure 1c).

Mariculture design and seagrass growth assessments

At the mariculture facility, which was housed in a covered greenhouse, four pools (INTEX®, W 1.2 m x L 1.2 m) were filled to a depth of 40 cm with 250 L of artificial seawater (Red Sea Salt) and 50 L of seawater collected from Langebaan Lagoon, to supply the plants with nutrients from their in-situ microbiome. The sediment-filled planting containers were then placed into the pools (Figure 3a). Each pool housed 12 planting containers, with six planting containers per core size ($n = 48$ cores in total, 24 per core size; Figure 3b). Salinity was maintained at 35 PSU and monitored twice a week using a handheld Red Sea™ Seawater refractometer. Each pool contained four ViaAqua aquarium glass heaters (150 W) to ensure that water temperature did not fall below 21 °C; Thermochron iButtons were used to monitor water temperature (which ranged from 21 °C to 25 °C). Mesocosm conditions broadly reflected those experienced by the plants in their natural environment.

Each pool was provided with five Dophin® C1600 Canister Filters and water pumps for aeration and filtration, which were cleaned weekly. Algae and dead leaves were removed by hand each week and a 20% water change (water purified through reverse osmosis made into a saline mixture of 35 PSU with Red Sea Salt) was performed. Additional light was provided by LEAF plant lights which were set to emit full spectrum

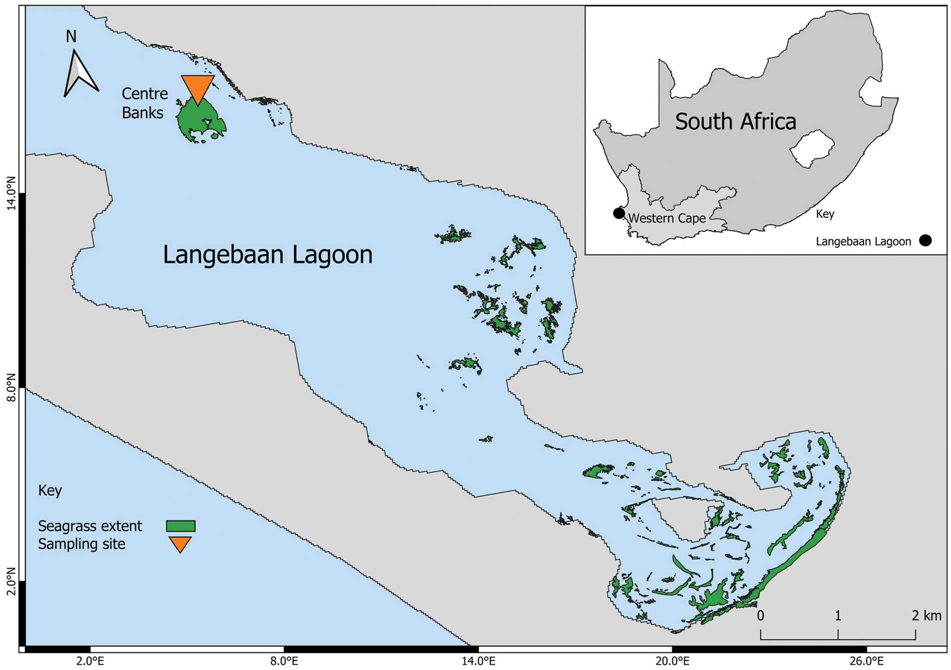


Figure 2: Location of the donor site at Centre Banks (orange triangle; 33°08'42.3"S, 18°03'43.0"E) in Langebaan Lagoon. Inset: Location of Langebaan Lagoon in South Africa. Data from Watson[24].

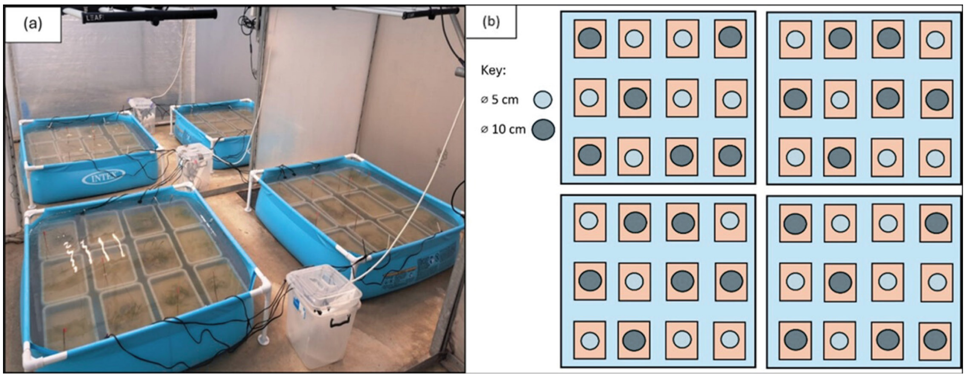


Figure 3: Mariculture facility experimental setup (a), with a depiction of the spatial arrangement of seagrass core sizes (b).

light (~303 μmol/m²s) for a 12:12 h light cycle. Seagrass growth was monitored for a period of 195 days, using measures of leaf length and shoot density. Here, we loosely use growth to describe changes over time in both shoot density and maximum mean leaf length. Leaf length was calculated by averaging the measurements of three of the longest leaves for each container, whilst shoot density was determined as the number of shoots per square centimetre. A monitoring protocol was established: at first, monitoring was conducted weekly for the first 53 days (except for between days 9 and 24), thereafter, monitoring was performed fortnightly for the remainder of the cultivation period (except for between days 100 and 124).

Statistical analyses

All statistical analyses were conducted using R Studio (version 4.3.2).[28] Prior to analyses, tests for normality and homoscedasticity were carried out using residual diagnostic plots as well as Shapiro–Wilk and Levene's tests, respectively. To investigate the effect of core size on seagrass shoot density (number of shoots per square centimetre) and leaf length (cm) across all pools, linear mixed models were performed using the *lmer* function in the *Lme4* package (version 1.1-35.4).[29] The optimal model structure was determined by selecting the model with the lowest Akaike's information criterion (AIC) value, following an assessment using the *anova* function. The optimal model included the response variables core size and pool as fixed factors, and the random effects of monitoring timepoint (number of days since transplantation as monitoring was temporally staggered post-transplantation) and planting container, as well as the interactive effect of core and pool. The main effects and the interactive effect of the model were assessed, with the *ggplot2* package used for all graphical presentations.

Results

Seagrass shoot density and mean leaf length changes over time

The first nine days of the experiment saw limited shoot density increases, followed by a large percentage increase between days 9 and 24, before growth remained steady until peak shoot density was reached between days 100 and 124. Similarly, leaf length demonstrated consistently gradual increases until maximum growth was reached between days 100 and 124, despite a decrease between days 31 and 39 and a large increase between days 53 and 68. Average seagrass shoot density for the 5 cm diameter cores was initially 0.04 ± 0.02 shoots/cm² (Figure 4a) and showed a ~200% increase (Figure 4b) in 100 days to reach 0.12 ± 0.07 shoots/cm², decreasing to 0.06 ± 0.04 shoots/cm²

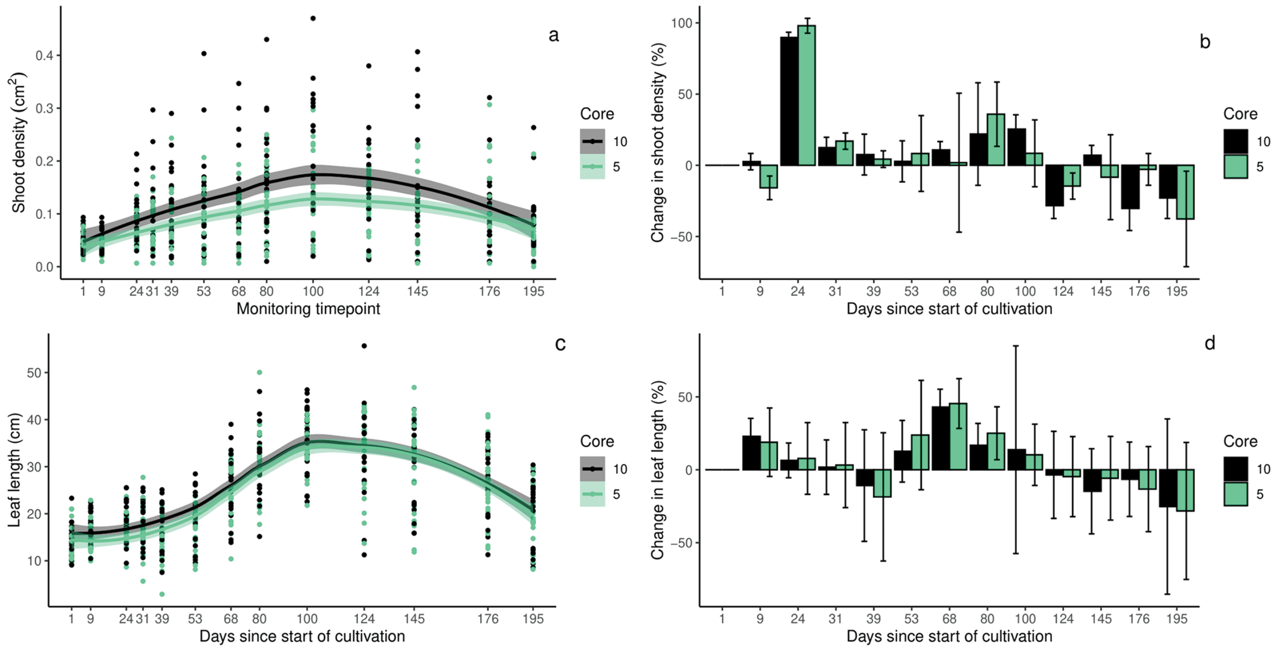


Figure 4: Mean changes in seagrass shoot density (a) and leaf length (c) as well as the relative percentage changes in seagrass shoot density (b) and leaf length (d) from one monitoring period to the next, across a 195-day period.

at the end of the experiment. Comparatively, average shoot density for the 10 cm diameter cores was initially 0.05 $\pm$ 0.02 shoots/cm^2 (Figure 4a) and demonstrated a ~300% increase (Figure 4b) to reach 0.20 $\pm$ 0.12 shoots/cm^2 after 100 days, but also decreased to 0.08 $\pm$ 0.06 shoots/cm^2 at the end of the experiment. The mean seagrass leaf length of the 5 cm and 10 cm diameter core sizes started at 12.94 $\pm$ 3.52 cm and 14.11 $\pm$ 3.33 cm, respectively (Figure 4c), before increasing by ~167% to 34.59 $\pm$ 5.04 cm and ~154% to 35.90 cm $\pm$ 3.33, respectively, after 100 days (Figure 4d), with both decreasing towards the end of the experiment to 19.35 cm $\pm$ 6.09 and 20.65 cm $\pm$ 6.70, respectively. Overall, both shoot counts and leaf lengths indicated peak growth was achieved between 100 and 124 days, after which shoot count and leaf length declined until the end of the experiment on day 195 (Supplementary figure 2 and Supplementary figure 3).

Effect of core size

Core size had a significant ($p < 0.005$, $X^2 = 8.50$, d.f. = 1) effect on seagrass shoot density (Supplementary table 1), as smaller cores had lower shoot densities over time in comparison to larger cores (Figure 4). Further, the effect of pool ($p < 0.005$, $X^2 = 38.55$, d.f. = 3) and the interactive effect of pool and core size ($p < 0.005$, $X^2 = 15.82$, d.f. = 3) also had significant effects on seagrass shoot density. Additionally, core size had a significant effect ($p = 0.04$, $X^2 = 4.08$, d.f. = 1) on seagrass leaf length (Supplementary table 2), as smaller cores were shown to have slightly smaller average leaf lengths; however, smaller cores did on average experience higher percentage increases in leaf length over time compared with larger cores (Figure 4). There was also a significant effect of pool ($p < 0.005$, $X^2 = 93.07$, d.f. = 3) on leaf length, but the interactive effect of core size and pool had no significant effect on leaf length ($p = 0.21$, $X^2 = 4.56$, d.f. = 3).

Discussion

Ex-situ mariculture of Zostera capensis*: Proof of concept*

Globally, seagrass populations continue to decline[1], including *Z. capensis* in South Africa[16,18], with urgent management intervention required to halt and reverse population losses. Previous in-situ restoration attempts have involved a trade-off between restoration success and impacts on donor sites, but ex-situ mariculture reduces disturbance to donor sites and increases restoration scalability by cultivating more seagrass biomass than that which was initially collected. Our work demonstrates a proof of concept of successful ex-situ *Z. capensis* mariculture, which found that *Z. capensis* plants, grown under controlled conditions, reach maximum growth between 100 and 124 days. Our results are further promising, given that plants grown under mariculture conditions can be 'hardened' to suit the conditions of the restoration site and have been found to exhibit better survivability than plants transplanted directly from donor meadows.[30]

Changes in leaf length and shoot density

Initially, the first 9 days of the experiment saw limited increases in shoot density, with some of the 5 cm cores even losing shoots, potentially linked to the disruption of the rhizosphere and microbiome, after collection and acclimation to mariculture conditions.[31] Subsequently, shoot density spiked between days 9 and 24, before growth remained steady until days 100–124. This consistent growth is likely a result of the plants capitalising on stable mariculture conditions, where temperature and light availability were controlled and physical disturbances were removed, compared to the more variable conditions in situ. Changes in leaf length followed a similar trend, despite a decrease from day 31 to 39, as growth was consistent until days 100–124. Steady increases in leaf length, with a spike in growth between days 53 and 68, could indicate seagrass plants transitioning from an intertidal morphotype to a subtidal morphotype. Seagrasses of the Zosteraceae family are known to exhibit plasticity to changing environmental conditions, with Manassa et al.[32] demonstrating the ability of *Zostera muelleri* to acclimate to changes in light and tidal exposure. The sustained increases in leaf length observed during the course of our experiment could thus be a result of the plants adapting to reduced light availability once permanently submerged. Interestingly, periods of peak shoot density increases correspond with periods of least leaf length growth and vice versa (Figure 4), potentially alluding to a trade-off between investment in lateral (shoot density) and vertical (leaf length) growth. It is possible that seagrass plants prioritised lateral growth at the beginning of the experiment (days 1 – 24) to capitalise on stable mariculture conditions before investing resources to sustain leaf growth.

Core size affects ex-situ seagrass growth

Investigating the effect of core size on seagrass growth is key to enhancing the efficiency of ex-situ restoration, given the balance between reducing core size to minimise disturbance to donor meadows and maximise restoration success.[10] Our results suggest that larger cores performed better than smaller cores, but further investigation is required to determine whether these differences persist following transplantation. This finding is consistent with that of an in-situ study by van Keulen et al.[33] in Western Australia, where larger core sizes (10 cm and 15 cm diameters) for *Amphibolis griffithii* showed significantly greater survival and growth post-transplantation in comparison to 5 cm diameter cores. Similar results were also observed in studies on *Syringodium isoetifolium*[34] and recently for *Z. capensis* in Mozambique[19]. Larger cores likely secure intact apical meristems and rhizomes, including the associated microbiome interactions and nutrients, which may enable faster and more persistent growth post-transplantation[35], although this remains poorly understood.

Limiting factors inhibiting Z. capensis *growth*

After peak seagrass growth between days 100 and 124, there was a decline in shoot densities and leaf lengths until the termination of the experiment on day 195 (Figure 4). Such a decline could be driven by nutrient deficiencies, resulting from our approach of using a closed-system aquarium design, given the inland position of Stellenbosch and the logistical challenges of transporting large volumes of seawater or sediment into our aquarium setup. Nutrient availability is an important part of seagrass growth and development, with Unsworth et al.[36] showing that nutrient additions of nitrogen, phosphorus and potassium (amongst others) led to a twofold increase in seagrass shoot emergence and leaf length. Additionally, the rhizosphere microbiome is known to be important for seagrass metabolite and nutrient exchange, but bacterial communities associated with seagrass microbiomes are often disturbed or removed when seagrass plants are uprooted during the transplantation process.[31] As such, it is possible that the disturbance of the microbiome during seagrass field collection and subsequent aquarium conditions might alter the capacity for seagrass nutrient uptake ex situ and be limiting seagrass growth beyond 124 days.

A framework for future seagrass restoration

The development of an effective means of upscaling seagrass restoration has recently been cited as a top priority for the advancement of seagrass conservation.[37] Ex-situ mariculture of the endangered *Z. capensis* presents an opportunity to maximise restoration attempts, without unnecessarily adversely affecting donor meadows, especially given the variable outcomes of previous restoration trials.[8,9] To build on the work presented here, we provide a framework to incorporate current guidance from published literature on seagrass restoration, and identify research gaps, which when addressed will improve restoration practices. The framework is organised into four phases: selection of recipient and donor sites, optimising ex-situ mariculture, selecting appropriate transplantation techniques, and effective monitoring of restoration success (Figure 5).

1. Selection of recipient and donor sites

Sites that have incurred sustained seagrass losses, but for which the stressors causing such losses have been mediated or removed, should be identified and prioritised for restoration[4], with comprehensive data on historical changes in seagrass persistence, loss, gain and recovery important to consider[24]. Ultimately, the success of a restoration project will depend on the management of stressors and whether a site can be returned to a favourable state for restoration, or whether the environment has been too drastically altered to sustain seagrass.[4] Once priority sites have been identified, information on the environmental drivers (such as light attenuation, sediment type, temperature and nutrient availability) affecting past and present seagrass distributions may be incorporated into habitat suitability models to determine if these sites will be receptive to restoration.[24] This is particularly important within a South African context, where *Z. capensis* is found in 37 estuaries, each with different environmental, ecological and evolutionary dynamics[16], which require a site-specific rather than a general approach to restoration.

Collecting site-specific donor plant material is important, as locally adapted plants are believed to be best suited to the conditions of the site being restored.[38] Selecting subtidal or intertidal seagrass ecotypes for restoration may also influence restoration success, as Wegoro et al.[34] noted a strong effect of depth in the restoration of *S. isoetifolium*; survival decreased with increased depth (due to decreased light availability). In South Africa, the consideration of evolutionary and population dynamics is a strong determinant of donor and source populations, as *Z. capensis* has defined population structure, even at small spatial scales (i.e. <50 km[39]). This is driven by low dispersal between populations along South Africa's high-energy coastline, which likely prevents genetic mixing, particularly in the absence of a strong seed base, resulting in unique population-specific signals. As such, moving cores between estuaries should be considered only as a last resort and in the worst-case scenario, in which populations have gone extinct.

2. Optimising ex-situ mariculture

This study has shown that *Z. capensis* plants can successfully be grown ex situ for transplantation but that the mariculture process requires further optimisation. For example, the use of open-water circulatory systems could stabilise the mariculture nutrient balance, whilst additional

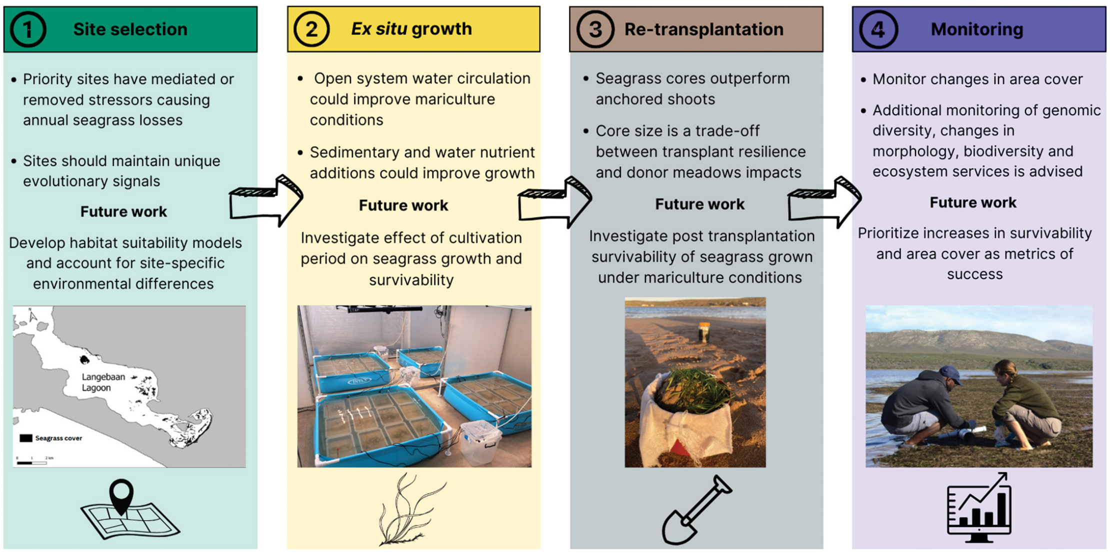


Figure 5: A framework for the advancement of future *Zostera capensis* restoration trials in South Africa, with considerations regarding site selection and donor material, leading to a successful restoration effort that can be monitored over time.

nutrients could be added to plant sediments to improve seagrass growth rates.[36] The cultivation period can also be altered to ensure optimal growth. For example, Zhang et al.[13] suggested that a 3–4 week cultivation period is best for land-based *Z. marina* mariculture, as the growth and survival of re-transplanted *Z. marina* plants was significantly reduced after a longer duration (9 weeks) of laboratory cultivation. However, if the land-based cultivation period is too short, then plants could be susceptible to physiological stress and increased energy requirements after transplantation into the field.[40] Given that peak *Z. capensis* ex-situ leaf length and shoot density were observed between 100 and 124 days (14–17 weeks), it is recommended that future studies should terminate the cultivation period at this point in anticipation of re-transplantation. Despite these promising preliminary results, our study focused solely on plants collected from one site. Further studies, incorporating plants from other South African estuaries, are required before the long-term viability of mariculture as a restoration technique can be determined.

3. Selecting appropriate transplantation techniques

Developing an appropriate transplantation method is an important consideration for maximising restoration impacts. Transplanted seagrass cores are known to have increased survivability post-transplantation in comparison to anchored shoots, as they minimise post-transplantation stress by reducing the effects of stochastic disturbance events.[8] Furthermore, the use of cores as opposed to anchored shoots involves a trade-off between achieving increased transplant resilience, as cores retain more of their microbiome, and reducing donor meadow disturbance. As such, the use of smaller cores reduces impacts on donor meadows, whilst allowing for increased transplant resilience.[41] However, smaller cores have been shown to have reduced in-situ survivability when compared to larger cores[9,19,33,34], unless they are planted at high densities (five to nine cores per 25 cm^2)[41]. Additionally, Watson et al.[8] also showed that compact planting patterns (i.e. dense and bullseye) promote long-term *Z. capensis* transplant persistence. The timing of transplantation should also be considered, with Mokumo et al.[9] showing that seasonality impacts the survivability of transplanted seagrass cores, as flooding during periods of high rainfall will hinder seagrass restoration in estuarine environments. Considering these findings in the context of the work presented here, we recommend that future studies investigate optimal planting density for transplanting 10-cm-diameter ex-situ-grown *Z. capensis* cores in compact patterns outside the rainy season.

4. Monitoring seagrass restoration success

Monitoring the persistence and change in area cover of re-transplanted seagrass is important to quantify project effectiveness, with the *Seagrass Restoration Handbook*[15] indicating that a long-term monitoring strategy (>5 years) is fundamental to assessing restoration success. It is recommended that structural (leaf length and shoot density), functional (increases in faunal richness) and genetic monitoring be incorporated into a comprehensive monitoring programme, in which successful restoration is assessed based on threshold values and quality ratios outlined in the *Seagrass Restoration Handbook.*[15] Assessing these metrics will strengthen insights into restoration success.[5] For example, genetic monitoring of changes in population allele frequencies can provide insights into the potential evolutionary resilience of restored seagrass populations and the consequences of reproductive processes following restoration.[38] Within a South African context, assessing all aforementioned metrics is likely to be too resource-intensive to implement at scale. Further, given that seagrass restoration in South Africa is in its infancy, we recommend, for comparability as well as applicability, that future studies adopt a similar monitoring protocol to Mokumo et al.[9] and Watson et al.[8] Priority metrics to guide restoration success should include biannual assessment of survivability and change in area cover, in addition to monitoring the fate of transplant holes in the donor meadows to better understand the impact of seagrass collection.

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Data availability

All data pertaining to this study are available on the von der Heyden Lab GitHub page at https://github.com/vonderHeydenLab/Z.capensis-mariculture-langebaan.

Declarations

We have no competing interests to declare. We have no AI or LLM usage to declare. A permit to collect seagrass and sedimentary cores within the West Coast National Park was granted by SANParks (CRC/2023-2024/018--2023/V1).

Authors' contributions

A.B.: Conceptualisation, methodology, writing – original draft, writing – review and editing, project leadership. K.W.: Conceptualisation, writing – review and editing, supervision. A.N.: Conceptualisation, writing – review and editing, supervision. S.v.d.H.: Methodology, writing – review and editing, supervision, project leadership, project administration, funding acquisition. All authors read and approved the final manuscript.

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