THE FIRST SUCCESSFUL USE OF A ROBOT SEED PLANTER IN SEAGRASS RESTORATION

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ABSTRACT

The global decline of seagrass meadows has intensified efforts to restore these foundational coastal ecosystems, yet restoration remains constrained by the inability to deliver seeds consistently, accurately, and efficiently over ecologically meaningful spatial scales. While underwater robotics have increasingly been proposed to overcome these operational bottlenecks, there is currently little empirical evidence demonstrating that robotic planting can achieve successful ecological restoration outcomes under field conditions. We evaluated the first application of a robotic underwater seed planter for seagrass restoration. A tethered remotely operated vehicle, equipped with a precision injection system, was used to deliver a bentonite-seed slurry into subtidal sediments at a target burial depth of 3–4 cm within a restoration site in Dale, West Wales. Over 31.5 hours of field operations, the system deployed 25,550 *Zostera marina* seeds across approximately 200 m^2. Eighteen months after planting, monitoring confirmed the establishment of at least 102 m^2 of seagrass meadow, representing approximately 51% of the original planted area. The established vegetation supported a mean shoot density of 56 ± 23 shoots m^{-2} and included reproductive shoots, demonstrating the completion of the reproductive cycle and indicating progression towards a self-sustaining meadow. The robotic platform achieved consistent seed placement while removing many of the operational limitations associated with diver-based restoration. These findings provide the first quantitative evidence that robotic precision planting can successfully establish seagrass meadows under field conditions. Although broader ecological constraints on restoration remain, robotic seed delivery represents an important technological advance that could substantially improve the scalability, repeatability, and safety of seed-based marine habitat restoration.

Keywords

Seagrass restoration; underwater robotics; ecological engineering; *Zostera marina*; seed injection; habitat restoration; autonomous systems; marine restoration; restoration ecology

INTRODUCTION

Seagrass meadows are among the most valuable ecosystems on Earth, providing essential ecosystem services that include supporting fisheries, stabilising sediments, improving water quality, storing large quantities of organic carbon and enhancing coastal biodiversity (Unsworth et al. 2022). Despite their ecological and socio-economic importance, seagrass meadows continue to decline globally as a consequence of coastal development, declining water quality, climate change and other cumulative anthropogenic pressures (Dunic et al. 2021; Waycott et al. 2009). Although some regions have shown encouraging signs of natural recovery following improvements in environmental management, restoration is increasingly recognised as an essential component of reversing historical habitat loss and meeting international biodiversity commitments (van Katwijk et al. 2016).

Over the past two decades, restoration techniques have advanced considerably, particularly through improvements in seed collection, seed storage, transplantation methods and our understanding of the ecological feedbacks governing restoration success (Maxwell et al. 2017; Unsworth et al. 2024; van Katwijk et al. 2016). Nevertheless, the spatial extent of restoration remains extremely limited relative to the scale of global seagrass decline. Most restoration projects continue to operate over relatively small areas because they rely heavily on manual field operations undertaken by divers. These activities are labour-intensive, expensive and constrained by weather, underwater visibility, dive safety regulations and the physiological limits of human operators. Consequently, one of the greatest challenges facing seagrass restoration is no longer determining whether restoration is possible, but how to deliver it efficiently at scales relevant to ecosystem recovery.

Seed-based restoration has emerged as one of the most promising approaches for achieving landscape-scale recovery because seeds can be collected in large numbers without damaging donor meadows and allow restoration over areas that would be impractical using adult transplants (Marion and Orth 2010; Unsworth et al. 2023). However, successful seed-based restoration depends on consistently delivering seeds to suitable sediment depths while minimising post-deployment dispersal, predation, and mortality. Maintaining this level of precision across large restoration sites is difficult using conventional diver-based techniques, particularly under variable environmental conditions.

Recent advances in underwater robotics provide an opportunity to address these operational constraints. Robotic systems are increasingly being deployed for marine inspection, infrastructure maintenance, ecological monitoring and environmental surveying (Cong et al. 2021). Their ability to maintain precise positioning, execute repeatable movements and operate safely for extended periods makes them attractive candidates for restoration activities requiring high spatial accuracy. Although robotic approaches to seagrass restoration have attracted considerable attention in both industry and the media, there remains little published evidence demonstrating that robotic planting can successfully establish seagrass under field conditions. Previous mechanised restoration approaches have largely focused on seed harvesting or mechanical planting devices requiring substantial diver intervention (Marion and Orth 2010; Orth et al. 2009; Paling et al. 2001) leaving an important gap in understanding the ecological performance of robotic precision planting systems.

The successful integration of robotics into restoration should not be viewed simply as an engineering challenge. Rather, it represents an opportunity to overcome one of the principal bottlenecks limiting the recovery of marine ecosystems. If robotic systems can deliver seeds with sufficient precision to achieve successful establishment while reducing operational costs and diver dependency, they could substantially increase the scale at which restoration can be undertaken. Importantly, however, technological innovation alone cannot overcome the ecological feedbacks that frequently determine restoration success (Maxwell et al. 2017). Demonstrating that robotic planting results in successful establishment under natural field conditions is therefore a necessary first step towards evaluating its contribution to large-scale ecosystem recovery.

Here we present the first field evaluation of robotic precision seed planting for seagrass restoration. Specifically, we test whether a tethered underwater robotic platform can (1) accurately deliver *Zostera marina* seeds into suitable sediments, (2) support successful meadow establishment under natural field conditions, and (3) produce vegetation that survives to reproductive maturity within two growing seasons. By coupling engineering innovation with ecological monitoring, this study provides the first quantitative assessment of whether robotic precision planting can help overcome one of the major operational barriers to scaling seagrass restoration.

METHODS

Study Site

The field deployment was conducted in a bay containing existing successful seagrass restoration activity in Dale, West Wales (Unsworth et al. 2024). A specific site, devoid of any pre-existing seagrass plants or seedlings, was selected for the planting trials to isolate the efficacy of the robotic intervention (Figure 1). All activities were conducted within an area licensed by the regional regulator, Natural Resources Wales, and the landowner, the Crown Estate.

Seed Collection and Preparation

Mature reproductive shoots of the seagrass Zostera marina were collected by hand by divers and snorkellers in August 2023 at Porthdinllaen, North Wales. The seeds within these shoots were subsequently separated over time using specialised aquaria facilities (Unsworth and Rees 2025) and stored in high-salinity, cold, clean seawater until use (Xu et al. 2020). Prior to planting, the seeds were subjected to a 6-hour freshwater pulse to enhance germination. They were then incorporated into a saltwater-based bentonite matrix (Güneri 2025). A 2:1 seawater-to-bentonite ratio was utilised to achieve sufficient viscosity for stable suspension and pump delivery, compensating for reduced clay swelling under saline conditions. Seeds were mixed into this cohesive matrix at a density of approximately one seed per millilitre.

Robotic Planting Platform

Planting operations utilised a tethered robotic seed planter (Grasshopper, ReefGen, San Francisco, CA, USA) designed for soft-sediment coastal restoration (Figure 2). This deployment followed initial laboratory and field trials conducted with a prototype robot in July 2022. The modular vehicle is equipped with a seed injection payload, onboard storage, navigation sensors, and topside control systems. Vehicle propulsion relies on eight electric thrusters configured for multi-axis manoeuvrability, precise station-keeping, and stable low-speed movement near the seabed, accommodating variable visibility and current conditions.

The planting payload features a 10 L onboard reservoir capable of storing approximately 20,000 seeds per deployment. Seeds are delivered through a downward-facing injector nozzle designed to place seeds beneath the sediment surface, minimising washout and improving seed-to-sediment contact. For this study, the mechanical depth setpoint was configured to local sediment conditions to maintain an exact injection depth of 3–4 cm. Real-time visual confirmation of injection quality was provided by an interior inspection camera adjacent to the injector assembly.

The robot was operated via a tethered topside control system that provided continuous command, telemetry, and live video feedback from a bow-mounted, forward-facing camera used for underwater navigation. Navigation systems incorporated globally referenced localisation to track vehicle position and orientation. Waypoint navigation and path-planning software guided the robot through predefined planting polygons to reduce operator navigation error. Additionally, fault-awareness systems continuously monitored vehicle and payload performance to support immediate in-field troubleshooting.

Field Deployment

During field operations, the prepared seed-bentonite matrix was loaded into the robotic planter. The matrix was delivered in discrete 4 mL injections, enabling consistent seed metering while limiting excess material deposition. The high-viscosity matrix effectively reduced post-injection dispersal and improved seed retention within the upper sediment layer.

Post-Planting Monitoring and Assessment

In October 2025, the aerial coverage of the establishing seagrass meadow within the original planting area was evaluated using a DJI Mavic 2 Pro drone equipped with an RGB camera, flown at an altitude of 50 m. The resulting imagery was aligned to ground-truth points established by divers.

In-situ ecological metrics were obtained by SCUBA divers along a 50 m straight-line transect traversing the continuous seagrass within the planting zone. Ten 0.25 m^2 quadrats were examined every 5 m to assess shoot density, percentage seagrass cover, average leaf length, percentage algal cover, percentage epiphyte cover, and percentage leaf blackening. Supplementary qualitative observations regarding the seagrass were also recorded by the observer.

RESULTS

Operational performance of the robotic planting system

The robotic planting platform successfully completed all planned restoration operations and consistently delivered the seed-bentonite matrix throughout the deployment period. A total of 25,550 *Zostera marina* seeds were planted during approximately 31.5 hours of field operations using a three-person operating crew. Individual deployment sorties lasted between 2 and 8 hours, with between 1,755 and 8,000 seeds delivered per sortie (Table 1).

Planting was undertaken across approximately 200 m^2 of seabed. Although the intended planting density was 25 seeds m^{-2}, clumping within the bentonite matrix resulted in a higher realised local seed density. Overall, the robotic platform achieved an operational planting rate of 6.35 $m^2\ h^{-1}$, corresponding to an average seed delivery rate of approximately 13.5 seeds min^{-1}.

Throughout the deployment the injection system consistently delivered the seed matrix at the target burial depth of 3–4 cm, with real-time camera feedback confirming stable operation under field conditions.

Meadow establishment following robotic planting

Robotic seed planting resulted in successful establishment of a new seagrass meadow within the restoration area. Six months after planting, abundant seagrass seedlings were observed throughout the planting site, confirming successful germination and establishment, although these were not formally quantified. Eighteen months after planting, drone surveys identified at least 102 m^2 of established seagrass within the original planting area (alongside field validation points), representing approximately 51% of the area initially planted. The restored meadow occurred as continuous vegetation rather than isolated individual plants, indicating successful spatial establishment at the site scale.

Characteristics of the restored meadow

Field surveys demonstrated that the restored meadow supported healthy developing vegetation. Mean shoot density was 56 ± 23 shoots m^{-2}, with an average seagrass cover of 9 ± 5% (Figure 3). Mean leaf length was 41 ± 17 mm. This shoot density is within the range of observed values at natural meadows within the same waterway (Bertelli et al. 2021). Indicators of plant condition suggested generally healthy vegetation. Epiphyte abundance, macroalgal cover and leaf blackening were all low, while no worm casts were observed during diver surveys. Together these observations indicate that the restored meadow was developing under relatively favourable ecological conditions.

Evidence of reproductive development

Importantly, reproductive shoots produced during the previous growing season were observed throughout the restored meadow eighteen months after planting (Figure 3). Completion of the reproductive cycle demonstrates that robotically established plants were capable of reaching reproductive maturity within two growing seasons. This finding indicates that the restored meadow was progressing beyond simple plant establishment towards the development of a potentially self-sustaining population.

Summary metrics

Across 31.5 hours of field operation, the robotic platform planted 811 seeds h^{-1} or 13.5 seeds min^{-1}. Planting was conducted across approximately 200 m^2, giving an operational planting rate of 6.35 m^2 h^{-1} and a realised mean seed density of 128 seeds m^{-2} (Table 2). Eighteen months after planting, at least 102 m^2 of seagrass had established within the original planting area, equivalent to 51% of the planted footprint. This corresponds to an effective establishment rate of 3.24 m^2 h^{-1} of field operation, or approximately 4.0 m^2 of established meadow per 1,000 seeds deployed. Based on the observed mean shoot density of 56 shoots m^{-2}, the established meadow supported an estimated standing population of approximately 5,700 shoots at the time of monitoring, equivalent to approximately 224 shoots per 1,000 seeds planted. These derived values should be interpreted as site-specific performance indicators rather than optimised production rates, but they provide a useful quantitative baseline for comparing future robotic seagrass restoration deployments.

DISCUSSION

This study provides the first quantitative evidence that robotic precision planting can successfully establish seagrass meadows under field conditions. By coupling an underwater robotic seed delivery platform with eighteen months of ecological monitoring, we demonstrate that robotic planting can achieve more than operational feasibility: it can result in the successful establishment of a developing seagrass meadow capable of reaching reproductive maturity.

While previous studies have explored mechanical approaches to seagrass restoration (Orth et al. 2009; Paling et al. 2001), evidence of the use of robots in marine restoration, and explicit linking of robotic planting to successful ecological restoration outcomes, has been lacking. Our findings therefore represent an important advance in integrating marine robotics with restoration ecology.

The significance of this work extends beyond demonstrating that a robotic platform can accurately place seeds beneath the sediment surface. Increasingly, the principal challenge facing seagrass restoration is not demonstrating that restoration is possible but delivering restoration efficiently without high failure rates consistently and at scales relevant to ecosystem recovery (Gräfnings et al. 2023; Unsworth et al. 2023). Manual restoration remains constrained by diver availability, weather windows, underwater visibility, safety considerations and the physiological limitations associated with prolonged underwater intervention (Sharma et al. 2023). Consequently, scaling restoration requires innovations that increase operational efficiency while maintaining ecological outcomes. Robotic systems offer one potential solution by providing highly repeatable seed placement, consistent burial depth and the capacity for extended deployment while reducing many of the operational constraints associated with diver-based restoration (Unsworth and Rees 2025).

More broadly, this study contributes to the growing recognition that restoration science is increasingly limited by operational scalability rather than ecological understanding alone. While ecological knowledge has advanced substantially over the past two decades, restoration programmes worldwide continue to operate at spatial scales that are several orders of magnitude smaller than the extent of habitat loss (Danovaro et al. 2025; van Katwijk et al. 2016). Closing this implementation gap will require technologies that increase restoration efficiency without compromising ecological performance. Robotic precision planting represents one potential mechanism for addressing this challenge by improving the consistency, repeatability and scalability of seed deployment.

Importantly, the ecological outcomes observed in this study indicate that robotic planting can support successful ecosystem establishment rather than simply successful seed deployment. Eighteen months after planting, over half of the original planting footprint supported established seagrass vegetation, with developing meadows exhibiting healthy shoot densities, relatively low epiphyte loads and evidence of successful reproduction. Although the restored meadow remains in an early stage of development, the presence of reproductive shoots is particularly encouraging, as it indicates completion of the reproductive cycle within two growing seasons. Achieving reproductive maturity represents an important milestone in restoration because it indicates that restored plants are beginning to contribute propagules to the surrounding environment and progress towards the development of a self-sustaining population (van der Heide et al. 2007). This highlights the increasing recognition that restoration success should be evaluated using indicators of ecological function and resilience, rather than solely the number of hectares planted or initial establishment rates (Unsworth et al. 2026).

The present findings also reinforce a central principle of restoration ecology: technological innovation cannot replace ecological understanding. Despite the precision of robotic seed delivery, approximately half of the planted area failed to develop into a persistent meadow during the study period. This highlights that restoration outcomes continue to be governed by ecological processes operating after planting. Seed predation, hydrodynamic disturbance, sediment instability, competition from macroalgae and the presence or absence of positive ecological feedbacks remain fundamental determinants of restoration success (Maxwell et al. 2017; Unsworth et al. 2023). Robotics can potentially and substantially improve the efficiency and repeatability of seed delivery (Unsworth and Rees 2025)**,** but they cannot eliminate the ecological bottlenecks that determine long-term persistence (van Katwijk et al. 2016). Consequently, advances in restoration engineering should be viewed as complementary to, rather than replacing, continued research into the ecological mechanisms underpinning successful ecosystem recovery.

Although the operational planting rate achi eved during this deployment should not be interpreted as representing the maximum capability of the robotic platform, the study demonstrates the practical feasibility of sustained robotic restoration under field conditions. This deployment was intentionally conservative, reflecting the developmental stage of the technology and prioritising operational reliability over maximum productivity. Future optimisation of vehicle navigation, mission planning, seed metering and injection frequency is likely to increase operational efficiency substantially. Similarly, refinement of the bentonite seed matrix to minimise clumping and improve spatial distribution of propagules may further enhance restoration performance (Unsworth et al. 2023). Consequently, the operational metrics presented here should be considered a baseline against which future generations of robotic restoration systems can be evaluated.

The broader implications of this work extend well beyond seagrass ecosystems. Numerous marine restoration activities, including restoration of saltmarshes, macroalgal forests, oyster reefs, coral reefs and other biogenic habitats, depend upon repetitive, spatially precise interventions undertaken in environments where diver-based operations are expensive, time-limited and often hazardous. Robotic restoration platforms therefore have the potential to become enabling technologies across a wide range of marine ecosystem restoration programmes. As underwater navigation, sensing technologies, machine vision and autonomous decision-making continue to mature (Bonin-Font et al. 2025), increasing integration of robotic systems into restoration practice appears likely. Future developments may include adaptive planting strategies that respond dynamically to environmental conditions, habitat suitability models and real-time ecological feedbacks during restoration operations.

Several limitations should be considered when interpreting these findings. First, the study represents a single restoration deployment undertaken at one site using a single seagrass species. Performance may differ under alternative sediment types, hydrodynamic conditions or climatic settings. Second, although operational performance was quantified, this study did not include a simultaneous comparison with conventional diver-based planting methods, preventing direct evaluation of relative efficiency or cost-effectiveness. Third, while monitoring over eighteen months demonstrates successful establishment and reproduction, longer-term assessment will be required to determine whether the restored meadow continues to expand, increase in density and exhibit the positive ecological feedbacks associated with resilient seagrass ecosystems. Finally, comprehensive economic analyses comparing robotic and manual restoration approaches remain an important priority for future work.

Despite these limitations, this study demonstrates that robotic precision planting has progressed beyond proof-of-concept engineering and can now be evaluated as a practical restoration technology capable of delivering measurable ecological outcomes. The greatest opportunity offered by robotics is not simply planting more seagrass over broader geographic areas, but enabling restoration programmes that are consistent, scalable, resilient and highly responsive to ecological feedbacks. As we strive to achieve global ambitions for marine ecosystem recovery, it is critical that we prioritise long-term, functional ecological outcomes over simplified short-term, hectare-centric performance metrics. Achieving this will require simultaneous advances in ecological understanding, restoration engineering, and adaptive management. Robotic precision planting represents an important step toward integrating these disciplines and provides a foundation upon which the next generation of large-scale marine restoration programmes can be built. The defining challenge of restoration over the coming decades will not be demonstrating that ecosystems can be restored, but developing the operational capacity to restore functional, self-sustaining ecosystems at ecologically meaningful scales. Tethered robotic platforms provide one empirical example of how advances in engineering can be integrated with ecological science to help close this implementation gap.

Conflict of Interest Statement

Author C. Oakes is affiliated with ReefGen, the company that developed the Grasshopper robotic seed planter evaluated in this study. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Access Statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request. All relevant summarised data are included within the manuscript and its associated tables.

Ethics Statement

This research did not involve human subjects, human data or tissue, or regulated vertebrate animals, and therefore did not require institutional ethical committee approval. All field activities, including seed collection and seabed deployment, were conducted with appropriate permissions and licensed by the regional regulator, Natural Resources Wales, and the landowner, the Crown Estate.

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Table 1: Summary of core operational parameters and resulting ecological metrics from the initial field deployment of the tethered robotic planter.

Metric	Value
Seeds planted	25,550
Operational time	31.5 h
Crew size	3
Area planted	200 m^2
Area established	102 m^2
Area retained	51%
Planting rate	6.35 $m^2\ h^{-1}$
Mean shoot density	56 ± 23 shoots m^{-2}
Mean cover	9 ± 5%
Reproductive shoots	Present

Table 2: Derived performance metrics, operational efficiency, and ecological establishment rates for the robotic seed planting operation.

Metric	Calculation	Value
Seeds deployed per hour	25,550 / 31.5 h	**811 seeds h^{-1}**
Seeds deployed per minute	25,550 / 1,890 min	**13.5 seeds min^{-1}**
Planted area per hour	200 m^2 / 31.5 h	**6.35 $m^2\ h^{-1}$**
Realised seed density	25,550 / 200 m^2	**128 seeds m^{-2}**
Established area	102 m^2 / 200 m^2	**51% of planted area**
Established area per hour	102 m^2 / 31.5 h	**3.24 $m^2\ h^{-1}$**
Seeds per established m^2	25,550 / 102 m^2	**251 seeds m^{-2} established**
Established area per 1,000 seeds	102 / 25.55	**4.0 m^2 per 1,000 seeds**
Crew-hours used	31.5 h × 3 people	**94.5 person-hours**
Person-hours per planted m^2	94.5 / 200	**0.47 person-hours m^{-2}**
Person-hours per established m^2	94.5 / 102	**0.93 person-hours m^{-2}**
Approx. standing shoot population	102 m^2 × 56 shoots m^{-2}	**c. 5,700 shoots**
Approx. shoots per 1,000 seeds planted	5,712 / 25.55	**c. 224 shoots per 1,000 seeds**

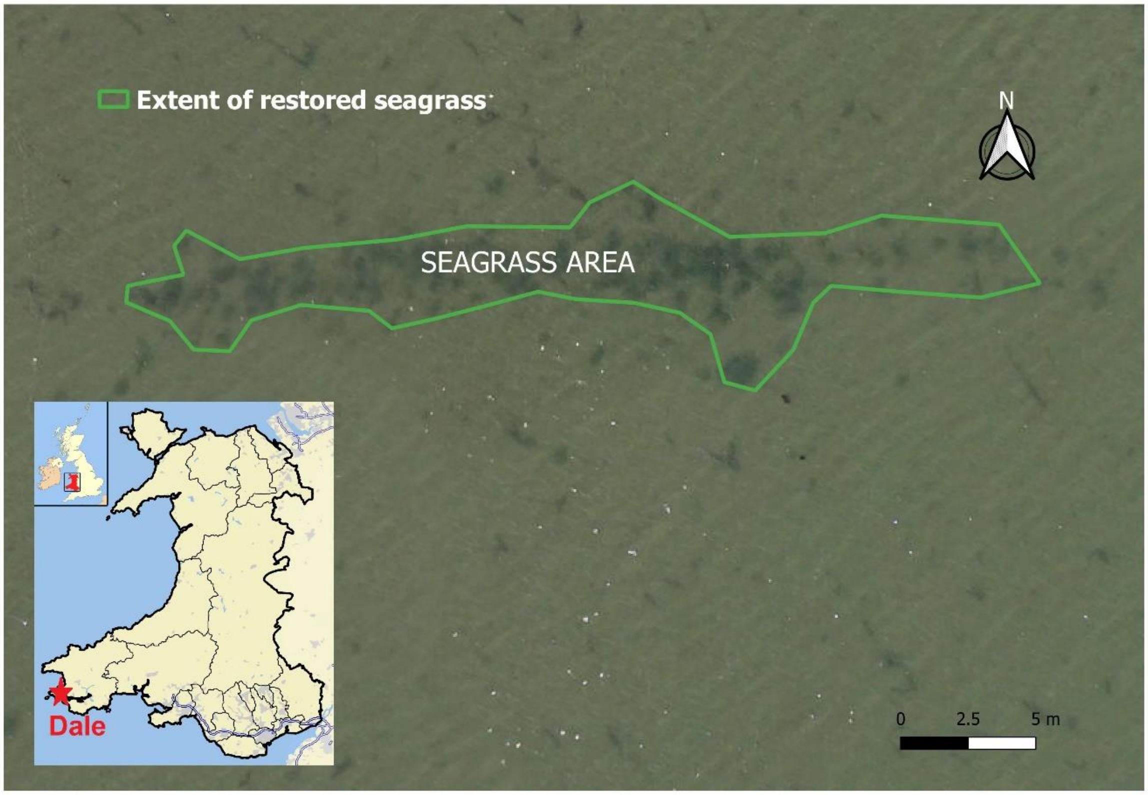

Figure 1. Location and spatial extent of the *Zostera marina* restoration site in Dale, West Wales. The main orthomosaic, derived from aerial drone surveys, depicts the delineated planting area (green polygon) containing the establishing seagrass meadow. The inset map indicates the regional location of the Dale study site (red star) on the southwest coast of Wales, UK.

Figure 2. Reefgen's Grasshopper vehicle functions effectively in sea states 1–2 and currents up to ~1.5 knots, with an operational depth range of ~0.3–30 m and a maximum speed of 2.5 knots (1.29 m s^{-1}). Power is supplied via tether (30 m, combined communications and power) or dual 12 V marine batteries (~350 W continuous draw). The system has a modular, field-deployable form factor (~30 kg) and can be transported in two airline-checkable cases, supporting deployment from small vessels (≥5 m).

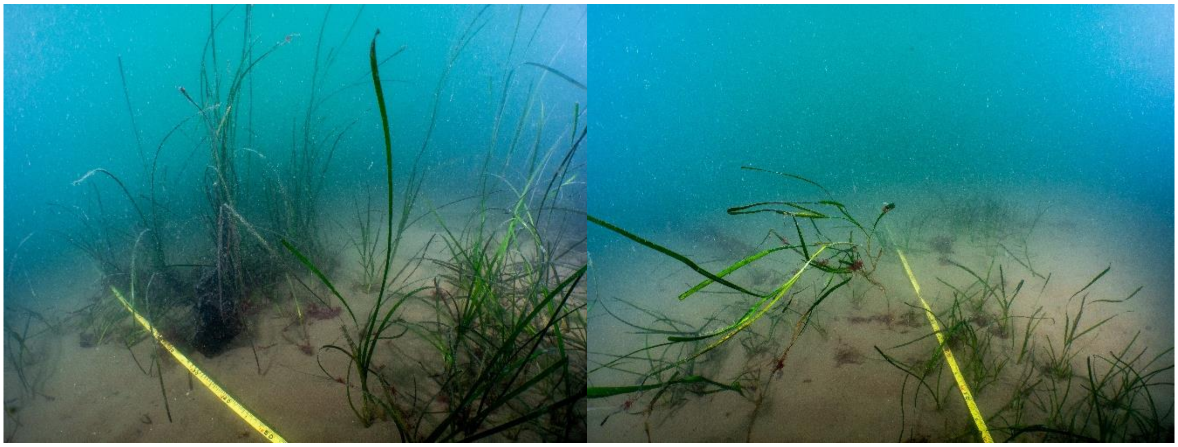

Figure 3. A) (left) seagrass patches, observed by SCUBA divers 18 months post-planting along a 50 m line transect, with long leaf length and low epiphytic coverage. B) (right) evidence of reproductive shoots with seeds. (Photos: Blaise Bullimore).