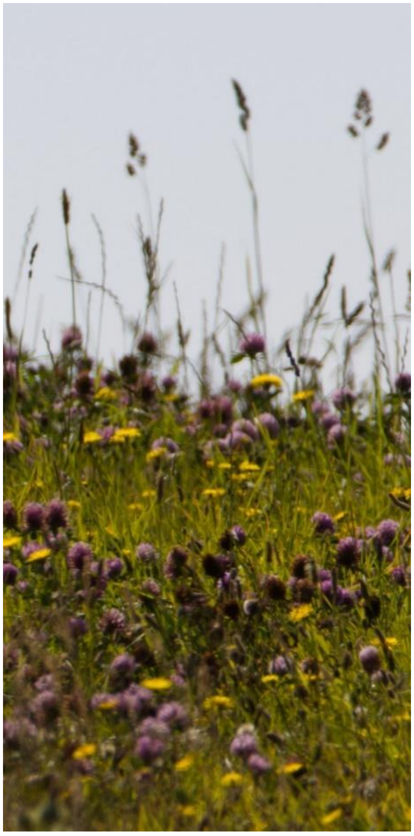
Establishment of Oioi (jointed wire rush) in Te Hakapupu

Final report for the *Toitū Te Hakapupu* project.



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Executive Summary

This report details an adaptive management experiment focused on re-establishing jointed wire rush ('oioi', *Apodasmia similis*) in the “South Arm” of Te Hakapupu (Pleasant River estuary), New Zealand. The project, a part of the larger *Toitū Te Hakapupu* initiative, addresses the degradation of saltmarsh ecosystems due to coastal development, farming, and the increasing threat of sea-level rise. The primary goal is to learn how best to reinstate oioi to provide essential ecosystem functions such as sediment stabilisation, water purification, carbon sequestration, and habitat creation for indigenous species, while also enhancing cultural and recreational values.

Background and Objectives: Saltmarshes in Aotearoa New Zealand are vital habitats that have been significantly reduced and degraded over time. Recognizing the urgent need for ecological restoration, this project aims to identify the most effective methods for re-establishing oioi, a key saltmarsh species. The experiment was designed to test various planting strategies and environmental conditions to optimize oioi survival, growth, and spread.

Study Area: The study was conducted in the South Arm of Te Hakapupu, an estuary that was partially reclaimed for farming in the mid-1950s. Restoration efforts began in 2009 with the reinstatement of tidal flows. The area is an important mahinga kai site for mana whenua, and the project aligns with *Toitū Te Hakapupu*’s broader efforts to improve the environmental health of the entire catchment. The experimental site features a mix of habitats, including glasswort meadows, pasture, and freshwater streams, providing a diverse setting to assess oioi performance under different conditions.

Experimental Design: The experiment employed a randomised design to assess the effects of elevation ('Levels') and plant spacing on oioi establishment. A total of 1,664 oioi plants were planted in 208 rectangular quadrats across four distinct ‘Areas’: ‘Inner’, ‘Mid’, and ‘Outer’ estuary areas, and along the banks of McWilliam ‘Stream’. Quadrats were positioned at two elevation levels: 'Upper' (landward side of the glasswort line) and 'Lower' (amongst the glasswort plants). Three spacing treatments were used: ‘Close’ (plant centres 0.25 m apart), ‘Medium’ (0.5 m), and ‘Wide’ (1 m). Sixteen additional ‘Wet’ quadrats were placed in the loose (unvegetated) sediment where they were covered in seawater every tidal cycle to test predictions that they would be washed away or fail to thrive. Quadrats were established in November 2022. Monitoring was conducted over three surveys in August 2023, May 2024, and February 2025, assessing variables such as plant presence, height, leaf colour, new shoots, lateral spread, browsing, flowering, and ground cover.

Key Findings and Discussion

- **Persistence and Survival:** Oioi presence was generally high across most quadrats, except in the Outer estuary area.
- **Browsing Impacts:** Browsing by stock, rabbits, and hares significantly affected oioi performance, particularly in the Outer estuary and along McWilliam Stream. Data from heavily browsed quadrats were excluded from subsequent analyses to minimize bias.

- **Leaf Colour:** Leaves in the Upper quadrats tended to be greener than those in Lower quadrats, suggesting better health and vigour. The proportion of dead leaves was higher in the Lower quadrats of the Mid and Outer estuary.
- **Growth and Lateral Spread:** Oioi leaves were longer in the Upper quadrats, especially in the Mid, Outer, and Stream areas. Lateral spread was limited, with plants in only a few quadrats merging to form continuous canopies.
- **Competition:** In Upper quadrats, competition from rank pasture grasses was a significant factor, with dense ground cover potentially smothering the oioi.
- **Flowering:** A higher proportion of oioi plants in the Upper quadrats produced new flowers compared to the Lower quadrats.
- **'Wet' Quadrats:** Oioi survival in the 'Wet' quadrats, located in frequently inundated and loose sediments, was poor, with high mortality rates and spindly growth.

General Conclusions: The experiment demonstrated that oioi establishment in South Arm has been achieved but that ecological performance varied significantly based on environmental conditions. Oioi survival, growth, and reproduction were consistently better in Upper quadrats, where soils are less saline and there is no tidal inundation. However, smothering of oioi by introduced grass may threaten the long-term persistence of oioi in the Upper quadrats. Oioi in the Lower quadrats of Inner and Mid areas of South Arm performed better than the Outer estuary, likely due to proximity to freshwater inflows and protection from strong tidal currents. Plant spacing had no detectable influence on oioi performance. Growth and spread has been relatively slow, so decades of managed and natural succession will be needed to fully capture the ecosystem services offered from restoring extensive oioi meadows.

Recommendations Based on the findings, the report provides several recommendations for future oioi restoration efforts:

1. **Prioritize planting in favourable zones:** Focus planting efforts on the upper margins of the saltmarsh, near freshwater sources, and in areas protected from strong tidal flows.
2. **Manage browsing:** Implement measures to exclude stock and control rabbit and hare populations to reduce browsing pressure.
3. **Control competition:** Once results from an ongoing field test are available, consider using graminicides to suppress competing grasses in the Upper quadrats, but monitor for potential negative impacts on oioi.
4. **Avoid planting in unsuitable areas:** Discontinue planting in sites that are inundated with seawater for much of the tidal cycle, as oioi survival is impossible in these conditions.
5. **Adjust plant spacing:** Plant oioi as close as practical together in areas where growth is expected to be slow and competition with other plants is a threat. Elsewhere and when the goal is to maximise the area to be colonised, plant 1m or more apart. Planting several widely spaced clusters of closely packed oioi represents an intermediate strategy to maximise landscape protection and enhancement.

6. **Monitor and adapt:** Continue monitoring oioi performance long after initial planting and adapt management strategies based on the observed outcomes.

7. **Investigate impact of soil salinity on root formation:** Evaluate whether planting with added topsoil helps oioi establish a stronger root system.

8. **Implement chenier sills:** Assess the effectiveness of Chenier sills in protecting plantings from wave action and promoting sediment buildup.

9. **Develop prioritisation model:** Create a model with all stakeholders for prioritizing planting sites based on agreed weightings of trade-offs of factors such as flood protection, sediment and nutrient reduction, biodiversity gains, mahinga kai opportunities, and the probability of establishment success.

10. **Promote knowledge sharing:** Continue to share findings and best practices with other restoration practitioners to improve oioi restoration outcomes across Aotearoa New Zealand.

Overall Significance This study provides valuable insights into the ecological requirements of oioi and the factors influencing its establishment in saltmarsh ecosystems. By implementing the recommendations outlined in this report, restoration practitioners can speed establishment and minimise costs of oioi restoration, contributing to the long-term health and resilience of coastal environments and the communities that depend on them. The *Toitū Te Hakapupu* project serves as a model for adaptive management and community-led restoration, demonstrating the importance of integrating scientific research with practical action to achieve meaningful conservation outcomes.

Contents

1. Introduction: the need for this adaptive management experiment

Those saltmarshes in Aotearoa New Zealand that remain relatively unmodified provide habitat for indigenous invertebrates, fish, and birdlife, and provide important ecosystem functions of sediment stabilisation, water purification, carbon sequestration and mahinga kai. The ecosystem health of saltmarshes, and estuaries more generally, is often degraded. Sometimes these habitats are removed altogether for coastal development and farming. Upcoming sea level rise because of climate change will increasingly disrupt coastal habitats and require the insertion of new roading and land stabilisation. There is therefore an increasing need to learn how to recreate and restore saltmarsh ecological communities throughout Aotearoa.

The adaptive management project described in this report was designed to learn how best to reinstate jointed wire rush (‘oioi’, *Apodasmia [Leptocarpus] similis*) in “South Arm” of Te Hakapupu (Pleasant River estuary), 5km northeast of Waikouaiti and 45 km north of Dunedin, South Island. Oioi is widely used for bioremediation and water flow management and is likely to have been present in South Arm before the estuary was reclaimed for farming in the mid-1950s. Te Hakapupu’s catchment is an important mahinga kai site for mana whenua. Establishment of a Marine Reserve in the lower reaches of the estuary and extending north along the coast is currently under consideration[1]. Restoration of the estuary and hill slopes around the Tūmai Beach farm park fits nicely within *Toitū Te Hakapupu*, a 5-year community partnership begun in 2022 to restore the wider Pleasant River catchment[2]. The project is jointly led by Kāti Huirapa Rūnaka ki Puketeraki and Otago Regional Council and is co-funded by the Ministry for Environment and Otago Regional Council.

The immediate goal to re-establish self-sustaining stands of *Apodasmia similis* in South Arm of Te Hakapupu, in order to:

- reduce the amount of sediment, nutrients and pollutants reaching the estuary
- sequester carbon to reduce climate change
- provide habitat for other endemic plants, invertebrates, fish and birds
- enhance cultural health of the estuary as a whole, and mahinga kai values in particular
- improve aesthetic and recreational appreciation of the area
- demonstrate responsibility and success of community-led biocultural restoration[3].

A review of literature and restoration practice[4] emphasised that establishing oioi in new estuary areas can be relatively difficult and unpredictable. It can be slow to propagate, requires dense planting to avoid later weed infestation, spreads relatively slowly (apparently mainly by vegetative reproduction), and occupies a relatively narrow zone towards the top of the estuarine-terrestrial ecotone. Spread deeper into intertidal zone is limited primarily by inability to grow in hyper-saline soils, prolonged

[1] South-east Marine Protection Forum (2018).

[2] The project aims to enhance the wider ecosystem, improve water quality by reducing the amount of sediment and nutrient input to the rivers and estuary, and use the best of Kāi Tahu mātauraka (knowledge) and modern science to sustain our efforts (Otago Regional Council, 2023).

[3] ‘Biocultural Restoration’ recognises the need to take of systems approach to ecological restoration, including building human relationships with place and economic resilience to allow communities to maintain their presence (Lyver *et al.* 2016, 2018, Akins *et al.* 2019).

[4] Young *et al.* (2023).

inundation with tidal flows, and displacement by water currents. It survives and grows better where freshwater flows dilute the saltwater. Spread further into terrestrial habitats flanking estuaries is potentially prevented by competition with faster growing species in more fertile soils, especially introduced grasses[5].

We took an 'adaptive management' ("learning by doing"[6]) approach to re-establishing oioi in South Arm. This choice was partly to progress actual restoration outcomes targeted by *Toitū Te Hakapupu* and the Tūmai Beach farm park, and partly to test alternative placement of the plants in a formal scientific way so that any lessons could be applied elsewhere in Te Hakapupu and more widely in Aotearoa. An experimental approach was also necessary in view of considerable uncertainty about drivers of oioi ecological performance and an absence of detailed local survey information on sea level inundation frequency and soil quality to guide precise placement of oioi planting. Our goal was to identify the fastest and least expensive method of reinstating oioi throughout available estuarine sediments and alongside a brackish stream that flows into South Arm[7].

2. Study area

A causeway was built over the entrance to South Arm in the 1950s to create paddocks for cattle and sheep farming (Figure 1). A Resource Management Act consent to create the Tūmai farm park subdivision in 2009 required reinstatement of tidal flows on South Arm[8] and ecological impact assessment and restoration plans suggested that oioi (Jointed wire rush, *Apodasmia [Leptocarpus] similis*) be planted around the newly reflooded areas[9]. There are no specific records of the vegetation in South Arm before tidal flows were blocked off in the 1950s, but it is logical that oioi existed there before being driven extinct by sheep and cattle browse and trampling[10]. The ensuing Tūmai Environmental Enhancement Plan identified reintroduction of oioi to South Arm as an important step to create a self-sustaining coastal subdivision and ecological landscape[11].

Since reflooding, there has been obvious spread of glasswort (*Sarcocornia quinqueflora*) outwards from the side of the estuary and gradual infilling of deep vehicle ruts formed when South Arm was used as a cattle and sheep run-off and when the causeway blocking its entrance was removed (Figure 2). There has also been a noticeable increase over the time of this experiment in the extent of *Schoenoplectus pungens* ('Three-square'), a native sedge. It grows in patches long the inland margin of the glasswort meadow, occasionally inundating the oioi planting quadrats. Fourteen patches of 'Salt Grass' (*Puccinella stricta*) were planted in November (2023). A few large specimens of the mākaka (saltmarsh ribbonwood, *Plagianthus divaricatus*) persisted along the edge of South Arm before the farm park development[12], and Tūmai residents have accelerated its recovery by planting 350 more stems in clusters within a 3-5 m strip along the entire 2.7 km estuary edge around the farm park in

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[5] Young *et al.* (2023).
[6] Walters & Holling (1990).
[7] We refer to this as "McWilliam Stream' in this report.
[8] Dunedin City Council (2008).
[9] Wildland Consultants (2007a,b,c).
[10] Grazing by cattle eliminated oioi from the margins of Northland dune lakes (Tanner 1992).
[11] Tūmai Beach Environmental Enhancement Group (2021).
[12] Moller *et al.* (2013).

2022 and 2023[13,14]. A diverse coastal saltmarsh meadow is developing: Occurrences of NZ Celery (*Apium prostratum*), Sea primrose (*Samolus repens*); Sea Blite (*Suaeda novae-zealandiae*), Native musk (*Thyridia repens*), Three-square (*Schoenoplectus pungens*), and southern coastal wind grass (*Lachnagrostis littoralis subsp. Salaria*) were noted close to or within the experimental plots monitored for oioi performance[15].

Anecdotal observations suggest that the inner reach of South Arm is now more regularly flooded at high tide times. If so, there has probably been a gradual flushing of the accumulated sediments out of South Arm, or at least a deepening of the main channels in the soft sediments to strengthen tidal flows.

All these biotic and biophysical changes signal that the entire South Arm ecosystem is in flux due to management intervention and lagged effects of reinstatement of tidal flows even 15 years after the causeway was removed.

Tidal water must travel around 1.6 km from the entrance to Pleasant River to reach the entrance to South Arm, and then a further 1.2 km to reach the top (southernmost reach) of South Arm. In neap tides the tidal water just reaches the top end and much of the glasswort on the estuary bed is not covered. On spring tides, the entire glasswort bed is covered. Much of the estuary bed below where glasswort now grows is a muddy ooze, especially close to the main water flow channels (Figure 2).

Some planting of oioi flanked McWilliam Stream that enters South Arm from the west around the middle of South Arm (Figure 2). This stream drains pasture on rolling hill country of North Tumai farm. Its outlet drains through a culvert inserted under a new causeway constructed in 2009 to define a new western margin of South Arm. That culvert has a one-way valve designed to let stream water out into the estuary during low tides, but to close at times of high tide to prevent seawater flushing back into the stream. This valve is only partially effective, so the water close to the exit of the stream is brackish. Pasture grasses are stunted in the vicinity of the stream bank and a sparse occurrence of glasswort indicates that the stream and adjacent soils are at least partly salinated. Heavy rain causes the stream to flood so that the area surrounding the stream margin is occasionally covered in standing brackish water. There are two further freshwater inflows to South Arm at the extreme southern (inner) end of South Arm Estuary (marked blue in Figure 3).

[13] Tūmai Beach Environmental Enhancement Group (2021).

[14] Many of these mākaka plants are growing strongly and spreading. They are beginning to shade 11 oioi quadrats by the end of the experiment. Recent appearance of mākaka along the western margin of South Arm, where there has been no restoration planting on that side, suggests that natural spread is important and fast.

[15] A more formal description of Te Hakapupu saltmarsh communities and comparison with other Otago saltmarshes can be found in Partridge & Wilson (1988b).

Figure 1: Overview of Tūmai Beach farm park at June 2021. Oioi planting experiments were conducted within and along the margins of South Arm, where tidal flows were reinstated in 2009 by removing the causeway constructed in the 1950s. Stock have been removed from the farm park and planting of native forest is underway in the long grass areas.

Figure 2. Oioi planting in South Arm of Te Hakapupu. *Top* - Most of the restoring estuary arm is a muddy ooze, dissected by main tidal channels and wheel ruts from earlier use as a paddock; *2nd row* – most quadrats were placed around the upper rim of glasswort beds flanked by grass banks; *Third row, left* – 12 'Wet' quadrats, each with 8 oioi spaced at 0.5 m, placed in the sediment below the glasswort bed; Third row right – An 'L-1.0 m' quadrat placed 2 m below the glasswort Upper edge; *Bottom, left* – McWilliam stream stratum; Bottom, right – Wet quadrat in McWilliam Stream zone 'G'.

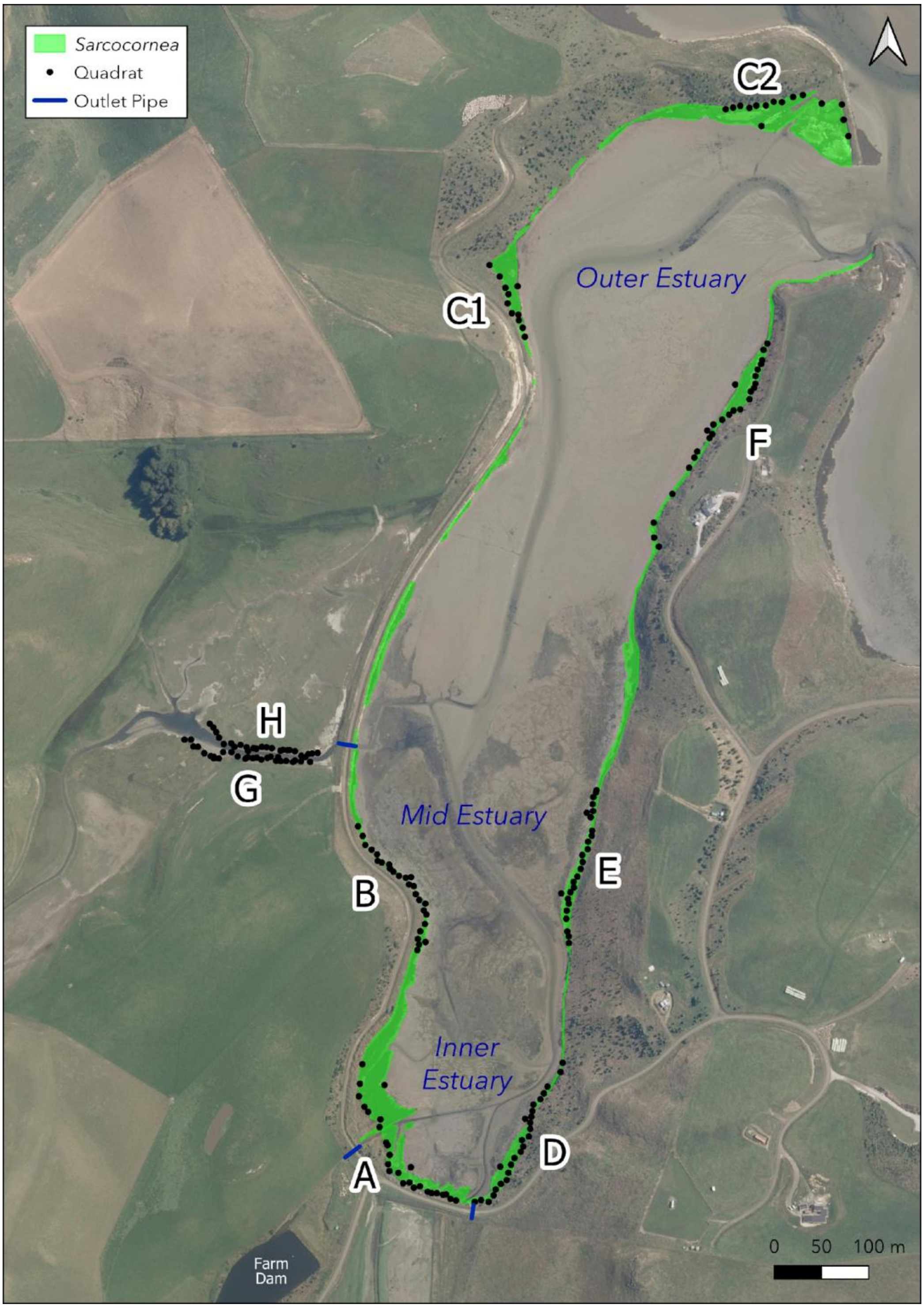

Figure 3: Arrangement of experimental oioi planting quadrats in four ''Areas'' around South Arm, Te Hakapupu. Each quadrat received eight oioi plants, spread equally across eight transects (A-H). Two transects were placed along the margins of McWilliam stream (the 'Stream' 'Area'), and two transects in each of three 'Areas' ('Inner', 'Mid' and 'Outer' Estuary) to stretch the experiment across maximum tidal inundation frequencies. Matching transects were placed on opposite sides of the estuary and stream. Transect C was divided in two because a stretch of steep and rocky shoreline prevented establishment of glasswort there.

3. Experimental design

3.1 Aims & predictions

The experiment aimed to determine optimum elevation (‘Levels’) and plant spacing to maximise survival, growth, and spread of oioi at South Arm, Te Hakapupu[16].

A review of research and best practice by restoration managers from around Aotearoa New Zealand[17] identified habitat selection and plant spacing as key determinants of restoration success. The review predicted that oioi planted in the highly saline soils under glasswort, and within the loose sediment beyond the glasswort meadow, would not survive and/or grow less than those planted on the unflooded margin of the estuary. It was also expected that competition with rank grasses growing on the landward margin of the estuary might eventually smother the oioi by competing for space, light, and nutrients.

Oioi copes well with freshwater inundation, and dilution of seawater by freshwater inflow may ameliorate any impacts of saline on oioi growth. Therefore, we included some planting alongside McWilliam Stream (Figure 2 & 3). Freshwater influences may also combine with threats to oioi persistence of being washed away in strong currents, so we hypothesised that oioi would do less well in the outer reaches of the South Arm where tidal flow is stronger and freshwater dilution is less.

Oioi restoration practitioners emphasised how much oioi success was site specific for reasons they did not fully understand. Accordingly, we spread the experimental treatments widely to test local constraints to reinstating oioi in South Arm of Te Hakapupu. The above predictions guided experimental design and maximised the success of establishing oioi in Te Hakapupu, but it is important to note that the exact outcome was unknown: it could be that some oioi established wherever they planted in South Arm; the rate of establishment, growth and spread might simply vary across treatments but still establish; or no oioi might establish anywhere.

3.2 Oioi propagation and planting

The oioi used in these experiments orginally came from stock grown at Mataī Nurserries, Waimate, in 2021. Puketeraki Native Plant Nursery purchased the plants in 7cm tubes and then split and repotted them into 1 litre pots in January 2022. They were then purchased for this trial and planted in November 2022. A height and diameter of free-standing leaves (i.e. not bunched together) of a subsample of the plants were measured just before the quadrats were established. The oioi averaged 647 mm high[18] and 67 mm diameter.[19] The plants had relatively well-developed roots, but were not root bound in their bags, so they were considered in excellent condition for planting out.

[16] A second and much smaller scale experiment to test whether seasoning of oioi plants in seawater prior to planting out could enhnace restoration success is still in progress. It will be completed in late 2026 or 2027. A third experiment started in April 2025 in which a graminicide spray was applied to suppress grass competition in half of the Upper oioi quadrats.

[17] Young *et al.* (2023).

[18] Range 320 – 900 mm, standard deviation 107 mm, measured on 80 plants.

[19] Range 20 to 120 mm, standard deviation 21 mm, based on two diametrically oriented diameter measures for each of 80 plants.

All oioi were blended before allocation to treatments, so there is no possibility that prior variation in the quality of the plants biased comparisons of performance between treatments.

Oioi were planted by 16 volunteers and Rūnaka kaimahi between 24 and 27 November 2022[20]. Pivots were cut to a spade width (ca. 160 mm) and depth (ca. 200 mm) in the substrate before inserting each plant. No fertiliser tabs or plant protectors were applied and there was no prior herbicide application to prepare the quadrat sites, but Glasswort and surface grasses were cut away in the vicinity of the plants before firmly bedding each plant in with the remaining sods dug out to position the plant.

3.3 Quadrats and experimental treatments

Altogether 1,664 oioi were planted in 208 rectangular 'quadrats', each with two adjacent rows of four plants (Figure 4)[21]. Sites for quadrats were arrayed randomly along a transect by selecting a random distance (between 5 to 9 m, pre-selected by computer). We paced out those distances along the shoreline (estuary) or stream (brackish) margin, and randomly allocated the treatments described below to each site until all treatments were balanced.

In the absence of water level records and an elevation map, we defined the estuary margin by the landward margin of the glasswort meadow. Quadrats were assigned to two 'Levels'' and three 'Spacing' treatments and positioned randomly along a transect in each of four 'Areas' (Figure 4)[22]:

3.3.1 Areas

We arranged 156 experimental quadrats within the South Arm itself, with equal numbers within three Areas: the 'Inner', 'Mid' and 'Outer' areas of the estuary (Figure 3).

A further 48 quadrats were placed along the flanks of McWilliam Stream to test oioi success in brackish conditions.

3.3.2 Levels

We mainly targeted our experiment on a very narrow strip along the margins of the restoring estuary. We had sufficient plants to test two contrasting 'Levels' (elevation and habitat zones), so we split most of the plants into two equal portions. One set was planted in quadrats on the landward side of this glasswort line (designated as the 'Upper' treatment), and the other in quadrats placed 2m below the glasswort line ('Lower' treatments) i.e. amongst the glasswort plants (Figure 4).

If oioi could survive in the loose sediments beyond the fringe of glasswort meadow, there would be considerable scope for accelerating spreading oioi throughout much of South Arm. However, many research and restoration teams suggested that oioi survival in this oozing and frequently flooded sediment is perhaps unlikely. We therefore decided to test their expectation, but only by placing a small number of (likely doomed) quadrats much deeper down the estuary sediment elevation and beyond where glasswort currently has reached. Two such 'Wet' quadrats, each with 8 plants spaced 0.5m apart, were placed at randomly chosen distances along each transect.

[20] Altogether we expended 179 hours labour for planting.

[21] A more detailed description of experimental rationale and design is provided by Moller *et al.* (2023).

[22] Detailed maps of all the zones are held by Kāti Huirapa Plant Nursery and Henrik Moller for detailed follow-up in future monitoring.

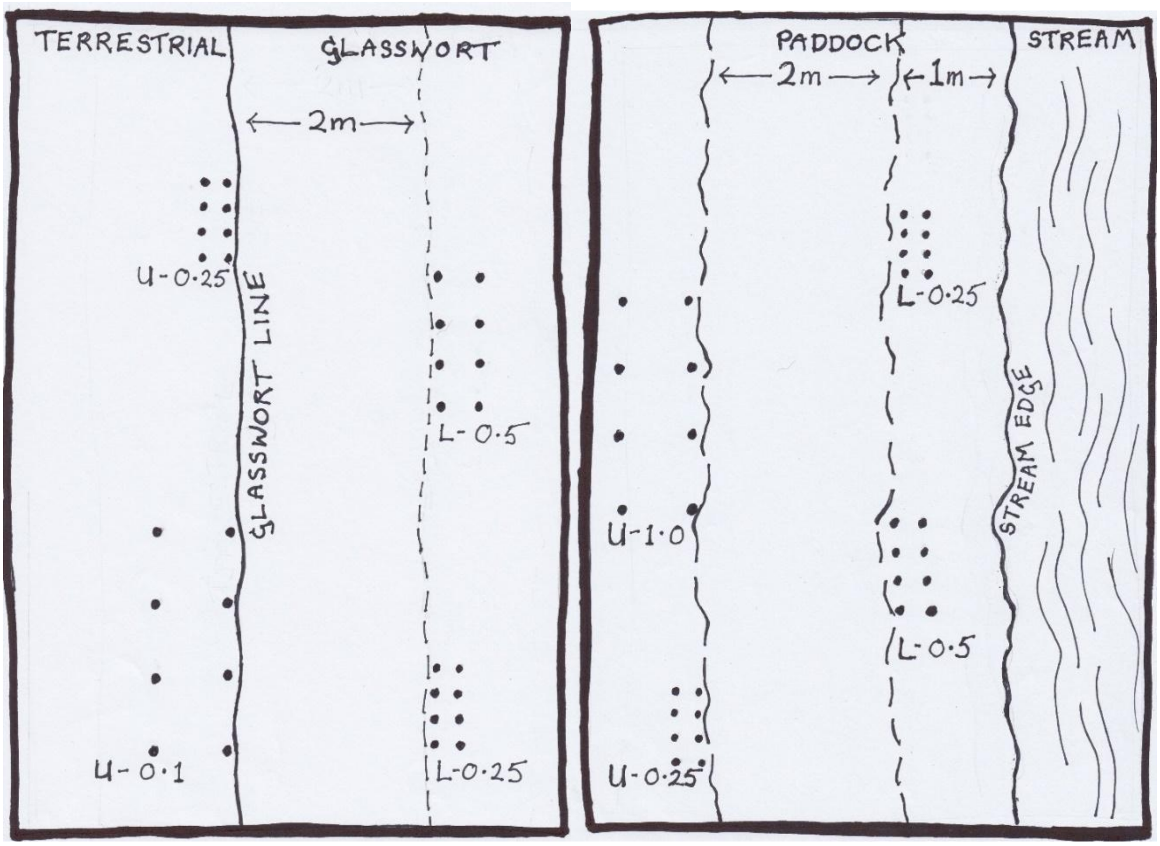

Figure 4. Layout of oioi quadrats along the South Arm estuary margin (left) and McWilliam Stream edge (right). There were 8 plants in each quadrat (shown as dots in the diagrams), planted either 0.25, 0.5 or 1 m apart. 'Lower' quadrats were at lower elevations and subject to more water or stream flow than 'Upper' ('U'). Quadrats were positioned randomly along the estuary or stream edge line.

The same principles used to design the estuary edge quadrat placements were used in the two McWilliam Stream zones, except that the upper edge of the water inundation zone was defined by the lip of the main streambed rather than the edge of the glasswort zone (Figure 4, right). Two quadrats were placed out in the stream bed in each of the two McWilliam Stream zones i.e. equivalents to the same 'wet' quadrats in the estuarine 'Areas'.

3.3.3 Spacing

Some oioi restoration teams elsewhere in Aotearoa simply spread the available number of plants evenly across an area targeted for restoration – this is part of a general approach of planting them "as close together as you can afford", partly to minimise weed incursion, and partly because interlocking of the plants and their roots is expected to give the oioi stand more resilience to erosion and displacement by water currents. Others followed standard horticultural practice that was normally used for grasses of leaving around 0.5 to 0.7 m between the plants. Most tried to space plants so they would just touch each other when fully grown, a target set to completely close cover and prevent or minimise weed incursions. The dilemma is that growth and lateral spread of oioi varies enormously[23].

[23] Reports varied from 2 to over 5 years to close the gaps of 0.5 and 0.75m between original planting (Young *et al.* 2023).

We had sufficient plants for just three treatments, so settled on 0.25, 0.5 and 1m spacings for the primary experiment and refer to these three treatments as 'Close', 'Medium' and 'Wide' spacing respectively in this report.

To avoid putting too many oioi plants at high risk of failure, all 'wet' quadrats had only one spacing treatment i.e. 'Medium' spacing (0.5m).

3.4 Monitoring response variables

The following response variables were measured at each quadrat on 4 August 2023 ('Survey #1), on 13 & 14 May 2024 ('Survey #2'), and finally on 13 & 14 February 2025 (Survey #3):

1. 'Presence' was measured from the number of oioi plants still standing in the quadrat. This was facilitated by the arrangement of 8 plants in a rectangle. Even if a few leaves remained or it appeared to be dead or dying, the plant was counted as present, so this is not a true measure of survival *per se*.
2. 'Height' (mm) of a single middle-sized oioi selected by eye from the remaining plants. The plant was gently stretched along a metal tape measure to measure the longest leaf in the plant.
3. The 'Colour' of the leaves was estimated by eye as a percentage divided between (i) 'Bright Green', (ii) 'Dark green or grey', and (iii) 'Dead' (the latter appeared straw coloured and broke off when handled). A single % colour estimate was recorded for the average over all oioi plants in the quadrat. Surface contamination by silt sometimes made this determination extremely difficult in 'Lower' and especially in 'Wet' quadrats, so we suspect that some of the leaves scored as dark green or grey were a brighter green underneath. A few apparently growing shoots had an yellow/gold tinge and were included in the Bright Green category.
4. The number of the plants with 'New Shoots' emerging from their base.
5. The number of plants with sign of 'Lateral spread' (new shoots emerging from the substrate away from the original plants[24]).
6. Whether or not the plants in the quadrat were now partially or wholly 'Merged' with their neighbours to form a continuous canopy.
7. The number of plants that showed any sign of 'Browse'. This usually showed as clipped off leaves, sometimes in a cluster of leaves or gnawed close to the ground (probably mainly browsed by sheep, rabbits or hares). Occasionally an single isolated leaf was observed (probably browse by rabbits, hares or insects). Some historical signs of browse in an otherwise healthy growing oioi was not counted.
8. The number of plants showing recent flowering – both male and female flowers were included but very old remnants of earlier flowering were excluded[25].
9. 'Other ground cover' was scored as a % of ground covered throughout the area between the 8 oioi plants within each quadrat by any species except glasswort. The weeds were most often introduced grasses and thistles, but a small low growing succulent Sea Blite (*Suaeda novae-zealandiae*) and 'three-square' (*Schoenoplectus pungens*) were also occasionally present in the 'Lower' quadrats of the estuary. Glasswort itself was not scored as it was considered part

[24] Oioi propagates vegetatively by sending out subterranean runners that then send up shoots in new whorls 10 or more cm from the parent plant. This variable was formally scored only in Survey #3.

[25] Flowering counts were only formalised in Survey#3. Flowering was present and noted sporadically in the earlier surveys.

of the experimental treatment and nearly always covered the entire area within the 'Lower' quadrats.

10. 'Other plant height' was measured as the maximum height of any other plants growing within or hanging over the Upper quadrats (usually grass, occasionally mākaka)[26].
11. 'Comments' were recorded less systematically for several quadrats, including the presence of algal mats or other flotsam on or around the oioi plants, sign of rabbit or sheep faeces in the immediate vicinity of the quadrat, and the name of species other than oioi and glasswort growing in or over the quadrat.

Measurement of these response variables designed for quick assessment. It became apparent that some of the oioi had 'thinned out' in successive surveys i.e. there were fewer leaves growing from the root base. Therefore, the above measures should be considered as an incomplete and relatively crude indicators of oioi performance. They are better at detecting relative differences between treatments than measuring the absolute survival, growth and spread.

3.5 Statistical analysis

We used the statistical programme 'R' to apply a stepwise algorithm to determine the best model to describe the variation in each oioi response between levels, area and spacing, and their interactions. Interactions are potentially important. For example, it could be that spacing matters little for oioi success in the more saline estuary sites, but becomes important in terrestrial margins of South Arm.

Formal statistical analysis was restricted to Survey # 3 data (February 2025) because (i) it was clear that differences were still emerging between treatments, (ii) there was better standardisation of the measurements (especially in scoring colour) by one monitoring team working together then, and (iii) some new variables were added for the final survey.

All the oioi in 'Wet' quadrats failed. Therefore, we excluded all the 'Wet' quadrats from statistical models to test for the main effects and any potential interactions.

Analysis involved the following steps:

1. All response variables were turned into proportions
2. Fit the model with all main effects and interactions.
3. Remove the term in the model that leads to the largest reduction in the Akaike Information Criterion (AIC)[27].
4. Repeat Step 2 until there is no reduction in AIC possible (and after each repetition, check if re-inclusion of any omitted terms leads to a reduction in AIC).

This identified the best and most parsimonious model to describe variation in oioi performance (Appendix A summarises the model results, including whether browse was filtered out for a given response variable). Figures 5-12 and 15 & 16 show the predicted 'Least square means' for the best models. The uncertainty bars are the "95% confidence intervals" for the means.

[26] Other plant height was scored only in Survey #3 as a prelude to an upcoming spray release experiment to relieve the oioi in Upper quadrats from competition with grass species.

[27] AIC is a statistical tool that helps us identify the best model by balancing two competing goals: how well the model fits the data versus how simple it is (in terms of the number of main effects and interactions it contains). The lower the value of AIC, the better the model achieves this balance (Johnson and Omland, 2004)

4 Results and Discussion

4.1 Persistence and survival

With the exception of quadrats in the 'Outer' estuary stratum, a high proportion of the oioi were still present (Figure 5). However, there were obvious differences in the health of the remaining plants which will be explored in the following analyses. Plants that were obviously struggling were defoliating and notably thinned out compared to those that were prospering.

4.2 Browsing by stock, rabbits and hares

Browsing of oioi was much more prevalent in the outer estuary and along the McWilliam Stream (Figure 6). Browsing showed as groups of adjacent leaves being sheared off at the same level (a bite), in extreme cases where nearly all the leaves were gnawed to ground level.

Fresh sheep and cattle faeces and hoof prints were found in the vicinity of the outer estuary and along the stream, and rabbit and hare pellets were found out on the glasswort meadow and in the pasture flanking the stream. Browse was particularly regular in zone C2 where the area was only partly fenced from stock; and along the McWilliam Stream because the electric fence placed to protect the oioi there failed to exclude sheep and cattle (Figure 3). A 2-3 week stock incursion occurred in zones D, E and F over the 2023 Christmas break when sheep breached a boundary fence and the farmer was absent.

Within these broad area differences, there was a consistent pattern for browse to be higher in 'Lower' compared to within 'Upper' quadrats (compare open and closed symbols in Figure 5). Often it was noted that browse in the Upper quadrats was more prevalent on the row of oioi closest to the glasswort meadow, so it seems that the stock, rabbits and/or hares fed on the oioi while exploring on the glasswort meadow itself.

This browse was unexpected and disrupted the experiment to some degree. It must have changed average leaf length, and removal of biomass may have affected the ability of the plants to grow new shoots, spread and flower. In severe cases, browsing may have killed the oioi. The relatively low presence of oioi in the 'Outer' estuary stratum is most likely to be caused by the more persistent stock browsing in zone C2 in particular.

We minimised the effect of browsing on oioi performance indicators in all the remaining analyses reported here by excluding data from all quadrats in C2, and data from individual quadrats elsewhere where more than half the plants showed sign of having been browsed. The best fitting models were indeed different for most of the response variables (Appendix A), so browsing certainly had considerable impacts on oioi growth and vigour. We caution that severe browsing may have made it more difficult to detect new leaves and lateral spread, and depletion of plant resources by earlier browsing may also have impaired growth at a later stage. Therefore, exclusion of quadrats with more than half the plants showing browse may have only partially filtered out its impact.

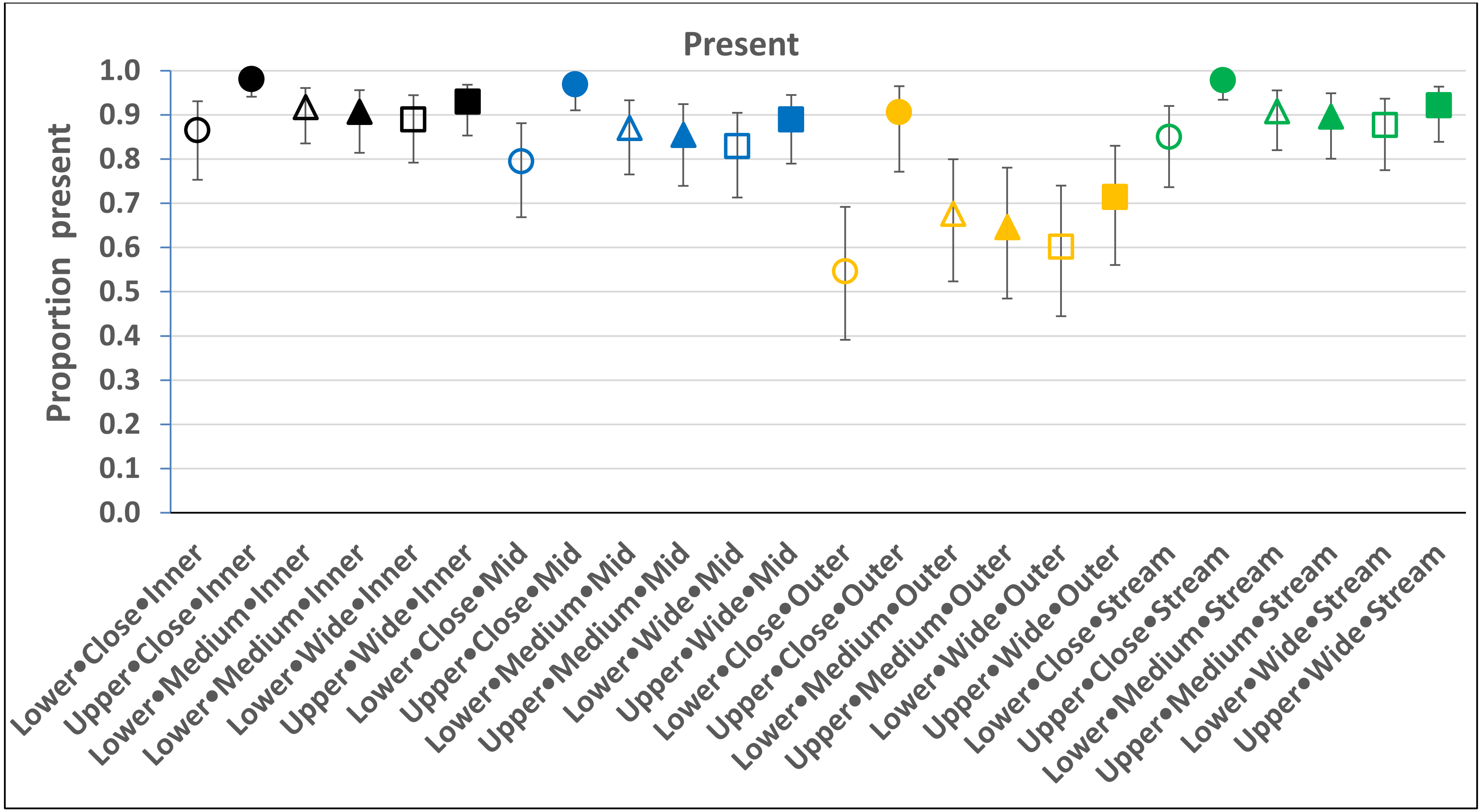

Figure 5. Proportion of oioi plants still present in quadrats by Survey #3 in February 2025. Presence within ‘Lower’ quadrats are shown open symbols, and within ‘Upper’ quadrats is shown by closed symbols. Presence within quadrats within the ‘Inner’, ‘Mid’, and ‘Outer’ estuary is shown in black, blue and yellow respectfully, and along the McWilliam ‘Stream’ in green. Presence within quadrats spaced where oioi were spaced ‘Close’, ‘Medium’ and ‘Wide’ are shown by circles, triangles and squares respectively. The error bars show 95% confidence intervals.

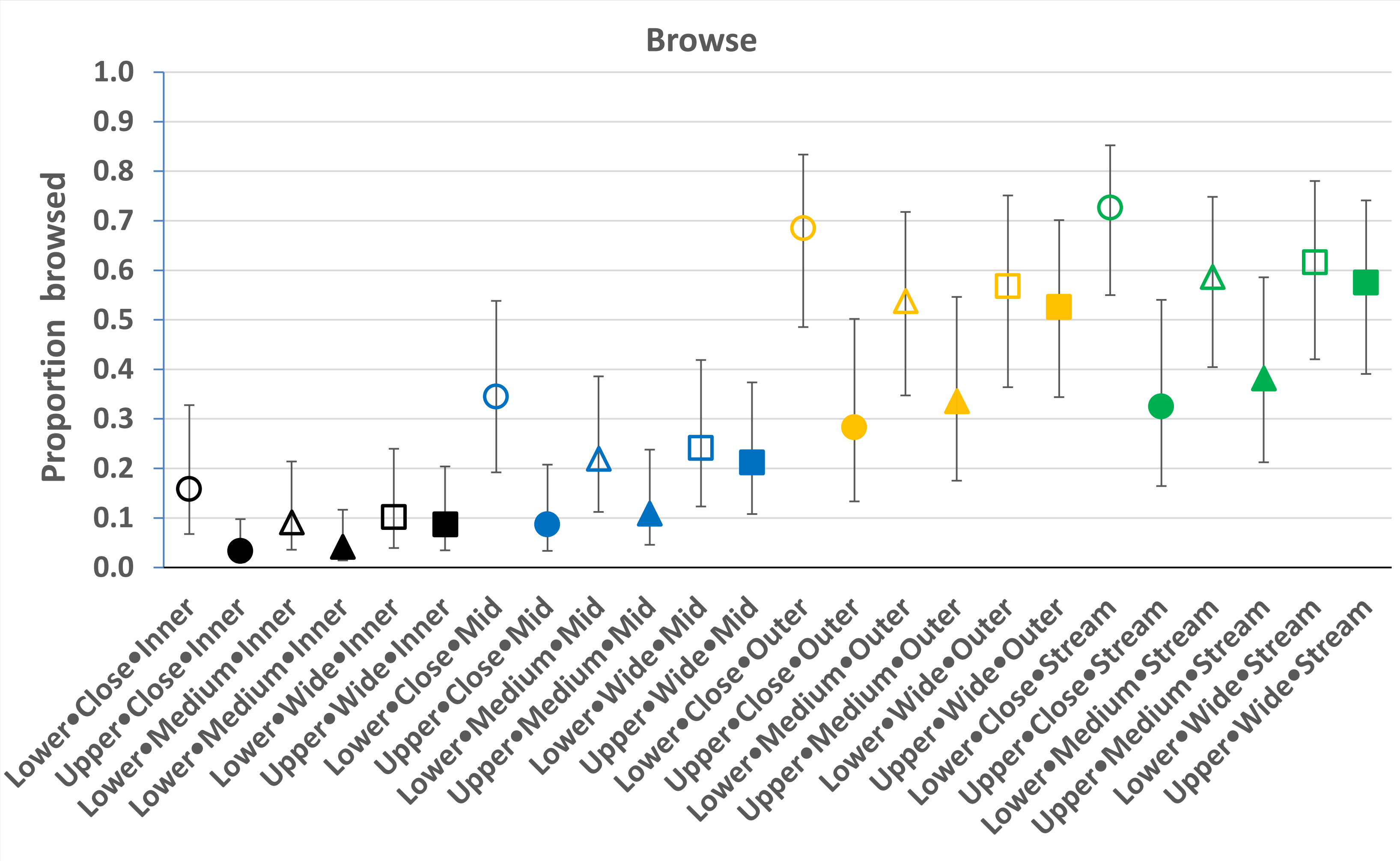

Figure 6. Proportion of oioi plants browsed by rabbits, hares and farm stock at Te Hakapupu. Browse within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Browse within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Browse within quadrats spaced where oioi were spaced 'Close', 'Medium' and 'Wide' are shown by circles, triangles and squares respectively. The error bars show 95% confidence intervals.

4.3 Leaf colour

There was a large variation in the colour of leaves, both within the same oioi plant, between the plants in a quadrat, and between quadrats in the same experimental treatment. Despite this variability, the average proportion of leaves within each colour band varied significantly between levels, and to a lesser extent between areas. Leaves tended to be greener at Upper than at Lower levels (Figures 8 & 9). This probably indicates improved plant vigour in Upper levels, but higher exposure to ultra violet radiation in the more open Lower levels might have also triggered production of melanin that darkened their leaves.

There was no sign of variation in colour of oioi leaves in different areas for Upper quadrats, but colour was brighter and there were fewer dead leaves in Lower quadrats placed in the 'Mid' and especially in the 'Inner' areas of the estuary. Colour of leaves along the Stream were about the same as in the Mid area of the estuary.

We found no evidence that oioi spacing effected leaf colour.

Scoring colour was difficult because tidal flow sometimes covered the leaves with silt, especially in the 'Wet' quadrats, but also in the Lower ones. A storm on 4-6 October 2024 triggered significant flooding at the Inner estuary end of South Arm and will have encrusted the leaves of oioi in Lower treatments with mud. Comparisons of the absolute proportions of Bright green vs Dark green and grey leaves must therefore be interpreted with caution as signals of plant health and vigour. Many of the leaves scored as dark green or grey in Lower quadrats may indeed have been healthy and growing despite being discoloured by silt.

Differences in measures of dead leaves are more reliable indicators of oioi performance because these leaves were often fragmented, shorter, straw coloured, and brittle (they broke when touched). There were more dead leaves on oioi in Lower levels in all areas except the Inner estuary (Figure 10). Death of leaves was lowest (around 15% of standing leaves) in all Upper quadrats and in the Lower quadrats in the Inner area of South Arm. About 40% and 70% of the standing leaves were dead in the Lower quadrats of Mid and Outer estuary.

The general pattern of relative differences between treatments for dead leaves is the inverse mirror of that for Bright green leaves (Compare Figures 7 and 9). This complementarity suggests that different rates of surface contamination by silt is not a sufficient explanation for the increasing proportion of bright green leaves in the inner and Mid areas of the estuary. The collective inference is that oioi health is best in Upper levels, and to be impaired most in the Lower quadrats within the Outer, Mid and Stream areas. Oioi leaf vigour is apparently moderately suppressed in the Lower level of the Inner estuary when compared against the optimum vigour demonstrated in all the Upper quadrats.

4.4 Growth and lateral spread

Oioi leaves were longer in the Upper level compared to Lower levels, especially in the Mid, Outer and Stream areas (Figure 10). Leaves were longer than when first planted in the Upper levels in the Outer estuary and along the Stream but elsewhere had about the same length or even shorter leaves than those on the original plants received from the nursery.

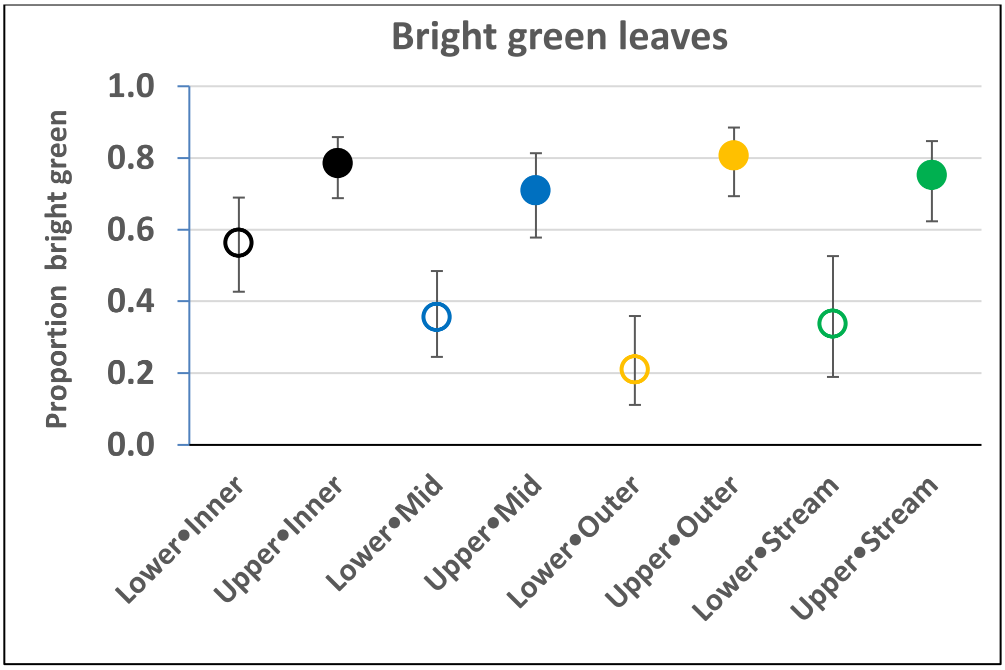

Figure 7. Proportion of leaves coloured bright green by Survey #3. Colour within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Colour within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. The error bars show 95% confidence intervals. There is a significant interaction between the main level and area effects (Appendix A).

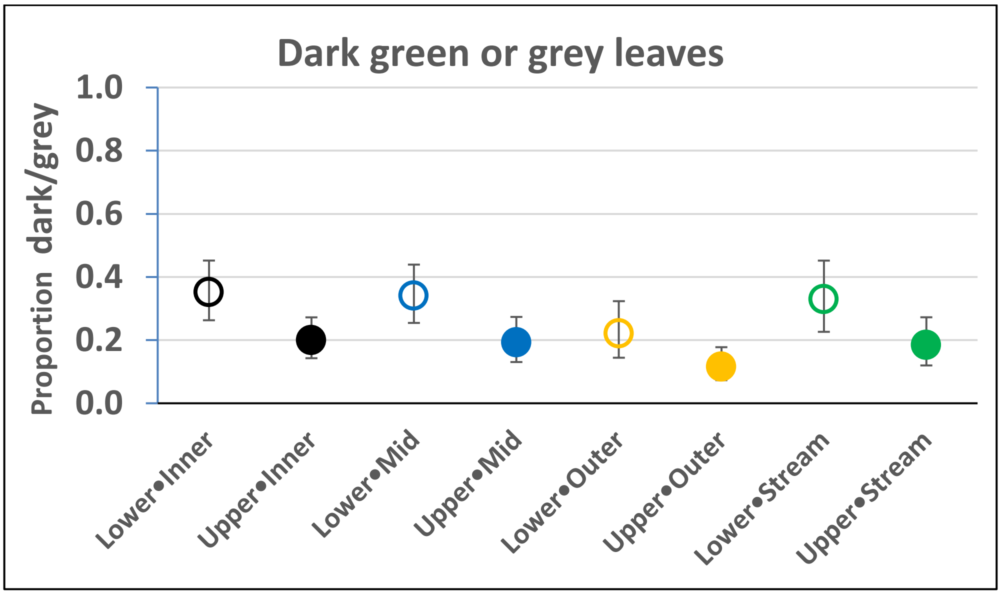

Figure 8. Proportion of leaves coloured dark green or grey by Survey #3. Colour within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Colour within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Data from C2 and quadrats with more than half the plants being browsed are excluded. The error bars show 95% confidence intervals. There is a significant interaction between the main level and area effects (Appendix A).

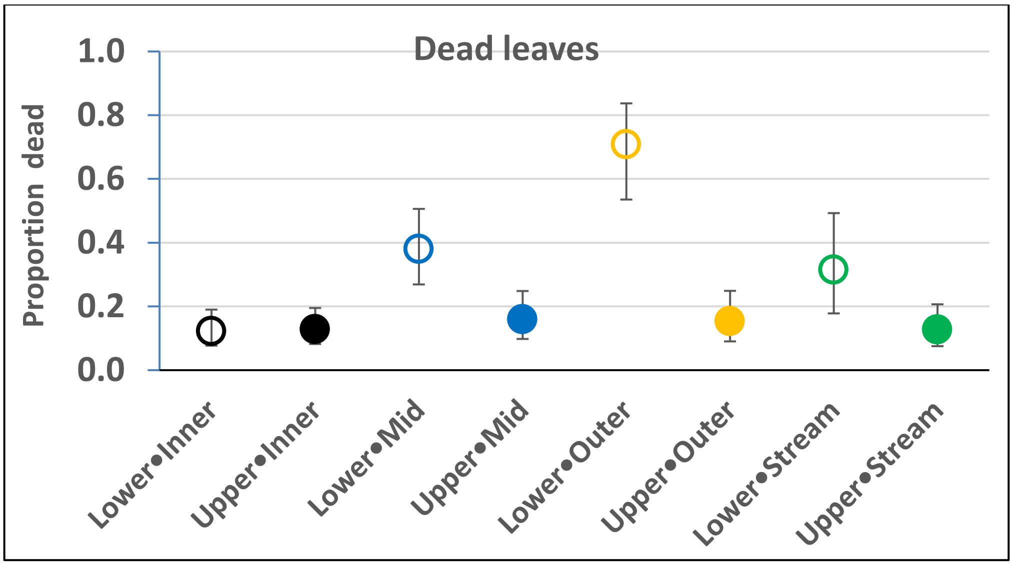

Figure 9. Proportion of leaves dead by Survey #3. Dead leaves within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Dead leaves within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Data from C2 and quadrats with more than half the plants being browsed are excluded. The error bars show 95% confidence intervals. There is a significant interaction between the main level and area effects (Appendix A).

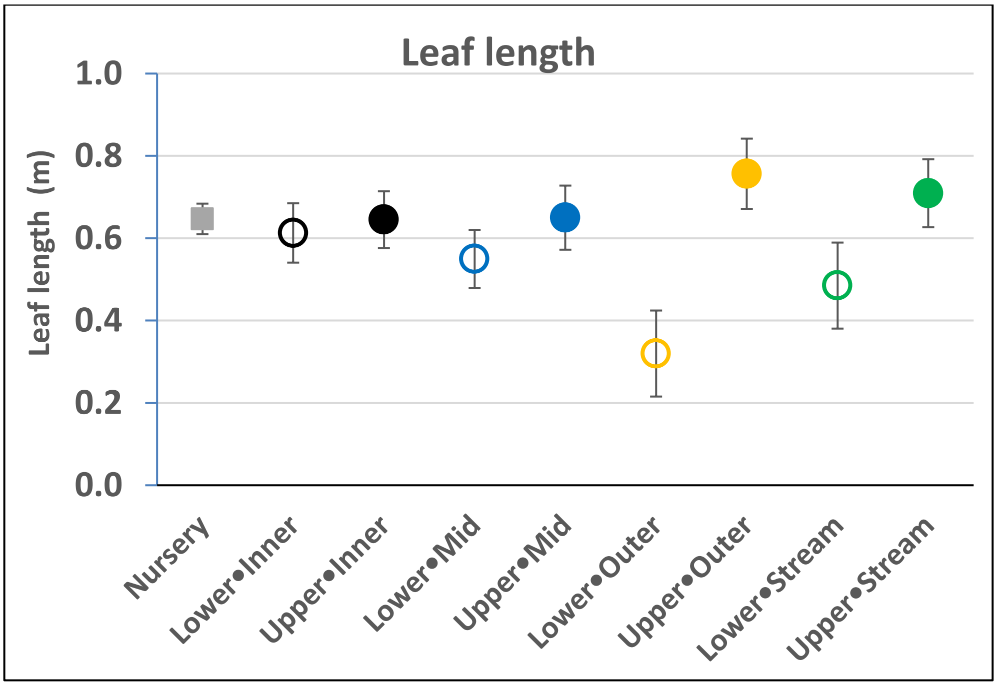

Figure 10. Leaf length of oioi (i) after growing in a nursery before planting out and (ii) by Survey #3. Leaf length at the time of planting is shown as a grey square. Leaf length within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Leaf length within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Data from C2 and quadrats with more than half the plants being browsed are excluded. The error bars show 95% confidence intervals. There is a significant interaction between the main level and area effects (Appendix A).

Reduction in leaf length in many Lower quadrats probably results from original leaves dying and falling off the basal whorl of the rush and the slow growth of new leaves, but some browsing effect may remain even after exclusion of data from C2 and other quadrats where more than 4 of their original 8 plants having been browsed.

New leaves were present on 80% - 100% of the oioi in Upper quadrats, but in fewer of the plants at Lower levels (Figure 10). Only 20%-40% of them had new shoots in the Lower quadrats in the Outer area of the estuary.

The proportion of quadrats showing evidence of lateral spread from the original plants was very similar to that for new leaves (compare Figures 11 and 12). It was very difficult to detect lateral spread from the oioi planted in Upper quadrats because the dense sward of grass obscured the base of the oioi, despite our best efforts to search at ground level. If this bias was strong, there would be an even more improved growth and spread of oioi in Upper compared to Lower levels than indicated by Figures 10 and 11.

All eight plants had spread laterally to become fully merged together in six quadrats (5 Upper, 1 Lower) and an additional quadrat (Upper) had partly merged oioi. All seven of these quadrats with merged plants were Close spaced (0.25 m apart at the centres). This equates to a lateral spread of just 10-15 cm over the 27 months since they were planted out, even in the most successful quadrats.

4.5 Potential competition from other plants

Nearly all the plants other than oioi in Lower quadrats were glasswort (Figure 13, Upper). Sea Blite being the next most common species. One Lower quadrat had three-square growing amongst the oioi.

Over 90% of the plants growing in quadrats in the Upper level were rank pasture grasses (Figure 13, bottom) – grazing by sheep and cattle was removed in 2009. A few quadrats at the extreme inner area of South Arm were overtopped by toetoe (*Ammophila arundinacea*), and some along the eastern flank had mākaka foliage intruding over the quadrat. We noted two quadrats where a thick mat of Sea Bite surrounded the oioi – a few leaves were emerging through the mat dense mat (Figure 14 top left)[28]. The Upper quadrats were placed right on the landward (upper) glasswort edge – sometimes it was noticeable that the grass growth and smothering of oioi was less in the seaward side of the quadrat.

Ground cover was extremely dense in Upper quadrats, so detection of the oioi and especially any new leaves and lateral spread was difficult and required careful parting of the surrounding grasses at ground level (see Figure 13, Bottom). In one quadrat we could not find any of the oioi, so they had been eliminated entirely by smothering grass.

The oioi were obviously much etiolated and spindly when in the dense grass sward (compare leaf length in Upper and Lower quadrats in Figure 10), but also occasionally had outgrown the grass sward in the scramble competition to capture light (Figure 14, bottom).

[28] It is possible that other factors suppressed the growth of oioi and this allowed the sea blite to entangle colonise the space between the rush, or perhaps they happily co-exist without affecting one another.

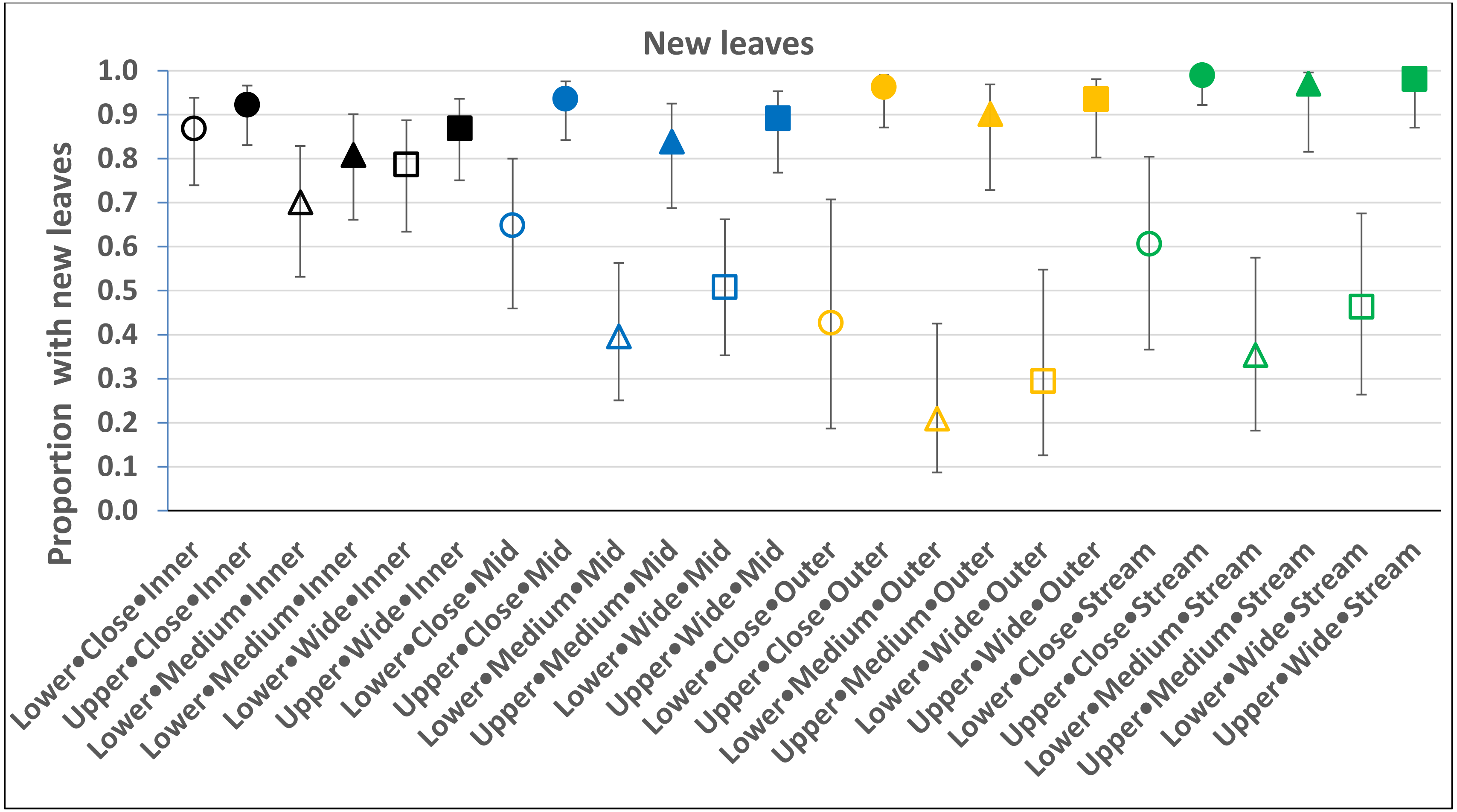

Figure 11. Proportion of oioi plants with new leaves by Survey #3 at Te Hakapupu. New leaves within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. New Leaves within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. New leaves within quadrats spaced where oioi were spaced 'Close', 'Medium' and 'Wide' are shown by circles, triangles and squares respectively. Data from C2 and quadrats with more than half the plants being browsed are excluded. The error bars show 95% confidence intervals. There are significant interactions between level and area main effects (Appendix A).

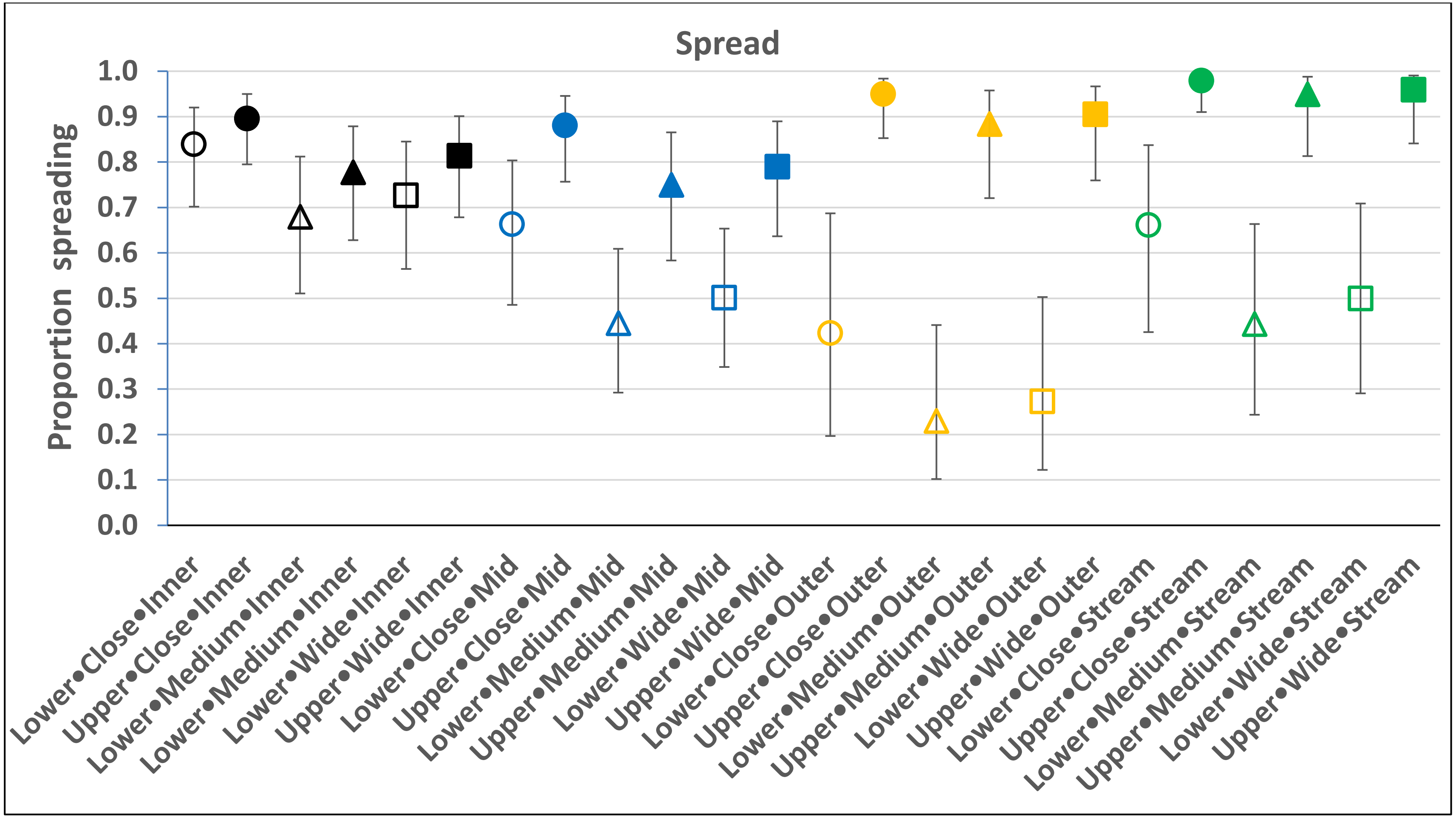

Figure 12. Proportion of oioi plants showing lateral spread by Survey #3 at Te Hakapupu. Spread within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Spread within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Spread within quadrats spaced where oioi were spaced 'Close', 'Medium' and 'Wide' are shown by circles, triangles and squares respectively. The error bars show 95% confidence intervals. Data from C2 and quadrats with more than half the plants being browsed are excluded. There are significant interactions between level and area main effects (Appendix A).

Figure 13. Some examples of surviving and growing oioi. *Upper*: The field team searches for lateral shoots in a 'Lower' quadrat amongst glasswort meadow. *Middle*: A vibrant bright green stand of flowering oioi an 'Upper' quadrat in an area with little introduced grass. *Lower*: The team searches for surviving oioi that are inundated with rank pasture grasses in an 'Upper' quadrat. It was sometimes slow and hard to work hard to find the plants in the long grass in Upper quadrats.

Figure 14. Some examples of potential impacts of other plants on oioi. *Upper left:* Oioi surrounded by Sea Blite. *Top right:* A mat of dead seaweeds washed into quadrats on the outer edge of the glasswort salt meadow. Lower: A rare example of oioi outgrowing rank pasture grasses in an 'Upper' quadrat (arrows indicate emerging oioi leaves).

Mats of dried seaweed were sometimes washed onto the Lower quadrats, occasionally flattening the oioi leaves (Figure 14, Upper right).

Approximately 80% of the ground within Upper quadrats was covered in other vegetation, compared to only 23% within Lower quadrats (Figure 15).

4.6 Flowering

A higher proportion of oioi plants had new flowers in the Upper compared to Lower quadrats (Figure 16). Flowering was markedly reduced in the Lower quadrats in the Outer estuary and partly reduced along the Stream. Browsing may have reduced detection of flowering.

4.7 Survival in Wet quadrats

Twelve quadrats were planted[29] at medium spacing in the loose and unvegetated sediments to test their survival and growth in extreme seawater inundation zones. Four quadrats were also planted within the main channel of the Stream areas[30]. Oioi clearly struggled there, so formal statistical model building was not pursued for these 'Wet' quadrats. Presence was reduced, especially in the higher flow and inundation areas: 9%, 19% and 56% of the oioi were still present by Survey #3 in the Inner, Mid and Outer reaches of South Arm respectively; and none of the oioi planted in the Stream were still present. Those oioi that remained were spindly, fragmented and often prone (Figure 17). Most leaves were classed as dead.

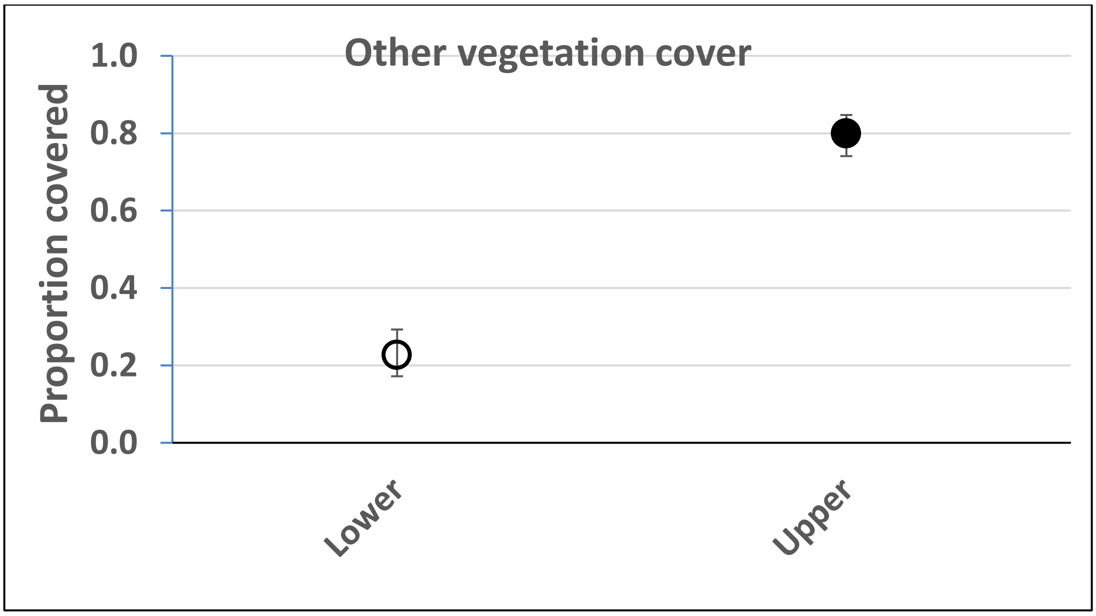

Figure 15. Proportion of ground covered within quadrats by other vegetation than oioi or glasswort at Lower and Upper levels by Survey #3. There were no spacing or area effects.

[29] Quadrats were 1-3 m on the seaward side of the glasswort meadow.

[30] Quadrats were within a metre of the lip defining the edge of the stream under most conditions).

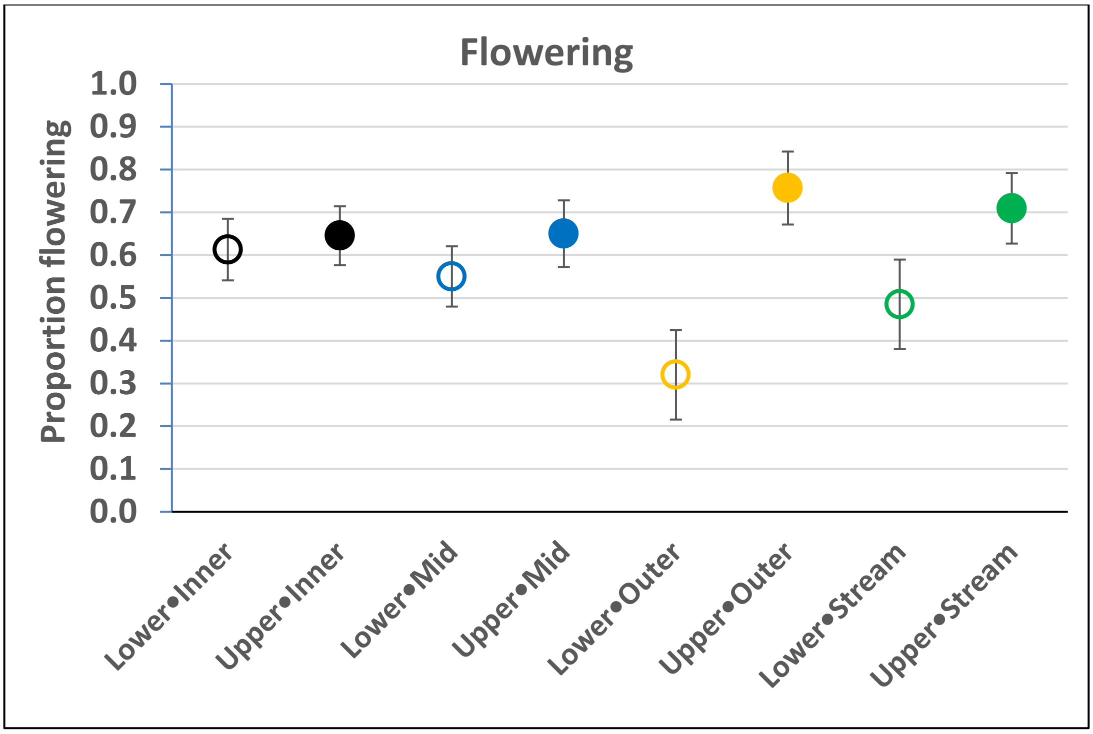

Figure 16. Proportion of oioi plants flowering by Survey #3. Flowering within 'Lower' quadrats are shown open symbols, and within 'Upper' quadrats is shown by closed symbols. Flowering within quadrats within the 'Inner', 'Mid', and 'Outer' estuary is shown in black, blue and yellow respectfully, and along the McWilliam 'Stream' in green. Data from C2 and quadrats with more than half the plants being browsed are excluded. The error bars show 95% confidence intervals. There is a significant interaction between the main level and area effects (Appendix A).

Figure 17. An example of a 'Wet' oioi quadrat in the Inner estuary area by Survey #3.

5. General discussion and Conclusions

5.1 What causes variation in oioi establishment and growth?

Establishment of oioi in South Arm has been achieved, but as predicted from our initial literature review and survey of oioi planters, its preliminary ecological performance varied greatly between quadrats. Oioi survival, vigour, growth, lateral spread and flowering were consistently higher in Upper than in Lower Quadrats, and better in the Inner and Mid areas of South Arm than in its Outer area. These area effects were only evident in the Lower quadrats which were placed in glasswort meadow – oioi performance above the saltwater inundation level seems to be excellent and relatively uniform, at least in the early stages of colonisation before the potential emergence of competition for space, light and nutrients with introduced grass.

Even within each of the same level and area treatments, there was remarkable variation in the health of quadrats placed even within 5 -10 metres of each other. Proximity to freshwater inflow and slightly raised ground are associated with better performance. Freshwater streams flow into South Arm's Inner and Mid areas where the Lower quadrats performed best, and smaller seeps of freshwater off the surrounding banks may have assisted growth of oioi in the vicinity[31].

Oioi performance along the flanks of the stream were intermediate between those measured in Inner and Mid areas compared to the Outer estuary. Unplanned grazing by stock disrupted measures of performance there. We did our best to filter out browsing impacts on performance metrics when building statistical models, but some depression of performance from browsing may still be reflected in the results. Establishment and improved vigour of oioi will not be secured until permanent and effective elimination of grazing occurs. McWilliam Stream is brackish and has widely fluctuating water flow. Sometimes the 'Upper' quadrats were standing in water for days and weeks on end because of flooding. However, the area surrounding the stream was subjected to full tidal flows before the mid 1950s when a causeway was inserted at the mouth of South Arm to 'reclaim' land for farming. A new causeway down the western flank of South Arm was built in 2009 to form a road and to continue exclusion of saltwater from the paddock through which the stream flows. The soils alongside the stream are probably heavily influenced by centuries of saltwater inundation before 1950, and these lag effects may still be reducing oioi performance there[32].

Short term field transplantation experiments concluded that salt-ladened soils prevented oioi penetration deep into salt meadows that are dominated by glasswort[33]. However, those same saline conditions prevented establishment and/or vigorous growth of introduced grasses and competition from grass often prevented upward colonisation of the terrestrial margins of estuaries. Therefore, the researchers concluded that oioi survival around the upper edge of southern estuaries was caused by release from competition with other species on its upper terrestrial margin, and prevention of downward colonisation by salty soils and seawater inundation on its marine flank.

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[31] Growth of Three-square and Batchelor Buttons also appears to be promoted in the patches with more freshwater.

[32] Andrew and Sarah McWilliam, who currently farm that remaining paddock, note that growth rate of the pasture grasses is much reduced there, but that the cattle and sheep greatly benefit from the feed, presumably because of elevated salt levels in the foliage.

[33] Partridge & Wilson (1988 a,b).

Our saltwater seasoning trial placed 80 oioi in planter bags sitting in a water bath with different concentrations of seawater for 33 weeks[34]. Oioi in more concentrated seawater had fewer bright green leaves, grew less, and produced fewer and much smaller new roots before being planted into the estuary. This experiment demonstrated that seawater directly reduces oioi performance even when initial plant health was good and they were rooted in high quality nursery propagation soil.

Some oioi planted in areas with higher water flux were apparently washed away soon after the establishment of our field trial. Other oioi planters from around Aotearoa had also observed such losses[35]. This vulnerability to high-flow conditions may reduce when a strong root mass has been established. Lateral extension from a closed canopy of oioi leaves may still be possible once the oioi mat itself starts to reduce water flow.

Spacing of plants was not identified as a significant variable in statistical model selections for most oioi performance measures. Also, any spacing effects were small and in opposing directions in those models where it was selected for consideration. Therefore, we conclude that spacing of the plants is unimportant in the early establishment phase of most restoration oioi restoration efforts.

Flowering was less prevalent in Lower than in Upper quadrats. It could be that the oioi plants respond to salt stress by diverting more of their available resources to vegetative growth than sexual reproduction.

5.2 Rate of establishment and spread

Poorer performance of oioi in hypersaline conditions was observed by our earlier field experiments[36], the anecdotal testimony of oioi planters from around Aotearoa[37], our saltwater seasoning experiment[38], and now by the results of the extensive field trial described in this report. However, these observations do not lead to a reliable conclusion that colonisation of the glasswort salt meadow at South Arm is impossible. Establishment and spread may be difficult but still achievable. If it succeeds, it might just be relatively slower in more saline conditions. There are extensive beds of pure oioi nearby at Merton in an arm of the Waikouaiti River estuary that receive regular tidal flows. Perhaps tidal flows have changed and the thick stands of oioi established before such changes? Perhaps gradual penetration into salty soils is possible by gradual lateral extension of the stand from a secure and flourishing oioi meadow that started on higher ground or in less saline soils? Or perhaps stronger flushing by freshwater from the surrounding land facilitated oioi establishment at Merton?

The proportion of the oioi leaves that were bright green was still climbing by the third survey analysed in full in this report, but this improvement appeared much earlier in the Upper than the Lower quadrats, and never in the Wet quadrats (Figure 18).

[34] Stirling *et al.* (2023).
[35] Young *et al.* (2023).
[36] Partridge & Wilson (1988a).
[37] Young *et al.* (2023).
[38] Stirling *et al.* (2023).

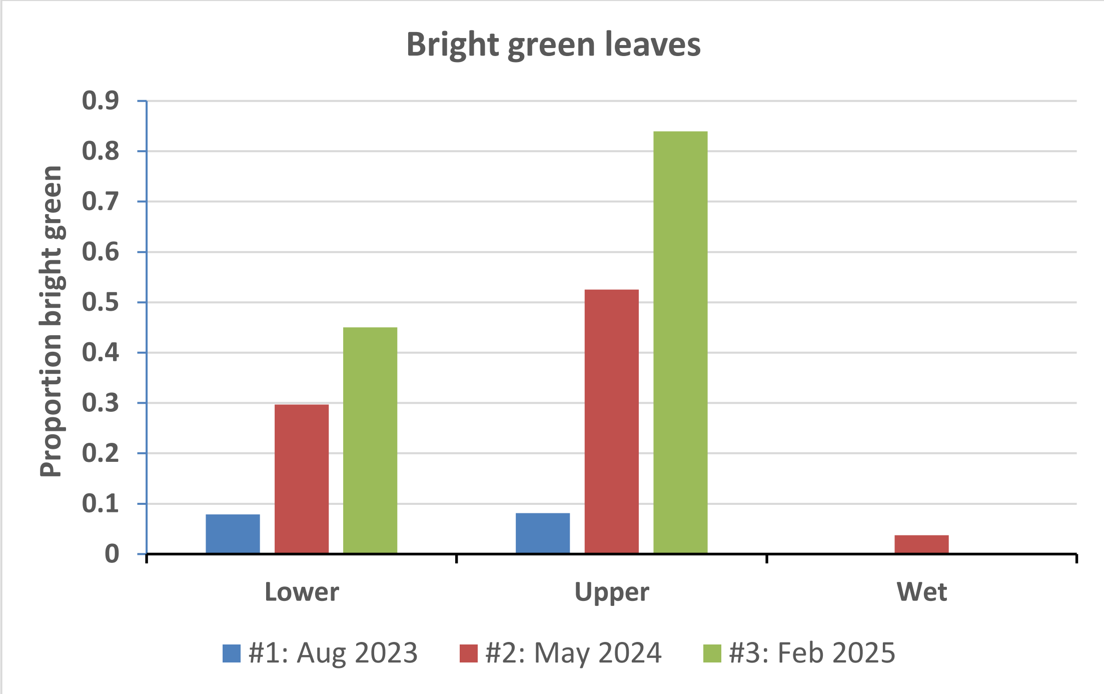

Figure 18. Proportion of oioi leaves that were bright green in different levels of Inner and Mid areas of South Arm in each of the three surveys conducted since initial planting in November 2022.

We restricted this analysis to quadrats in the Inner and Outer area because of the other indications that performance in the Outer and Stream areas is particularly impaired, especially in Lower quadrats, and perhaps partly because of browsing interference.

It is possible that the oioi in the Lower quadrats will eventually attain the same vigour as those in Upper quadrats, but only future surveys can determine whether the treatment effects we report now indicate establishment and subsequent growth is forever poorer or just slower in more saline conditions. It would be useful to know which of these alternative outcomes will eventuate because most of the 27 ha of South Arm is currently a bare substrate (Figure 2, Top)[39]. If it can eventually be colonised by oioi, ecosystem functions provided by the plants can be greatly enhanced.

We monitored the fate of well-grown and healthy oioi plants grown to near full height in ideal propagation soils packed in 'PB3' planter bags[40]. Approximately 1.8 litres of nursery soil was packed around each oioi root bolus when planted into the estuary. The plant's initial stored energy, nutrients and biomass, and the nursery soil presumably sustained the plants in their new environment at least for a short while. Based on her experience with growing a wide variety of plants in nursery conditions, Angelina Young expects the nutrients in the PB3 planter bags was probably exhausted in the 6 months immediately after planting. If so, the oioi growth we observed after Survey #1 is likely to have been sustained by capture of new nutrients and lateral and vertical extension of their root mass. In Angelina's experience, oioi flourishes once it has room for lateral spread. When we broke open the

[39] The surface is also still scarred with tractor ruts formed in 2009 or earlier before South Arm was reflooded, so establishment of an oioi meadow will add aesthetic apeal.

[40] A small number were grown in 1 litre plastic pots.

planter bags to establish the quadrats, lateral shoots were visibly strong and robust. Therefore, the plants were probably constrained less by available nutrients in the soil than by space to spread through this vegetative process. However, all plants take some time to extend roots into their new substrate and adapt to new conditions when first transplanted. Therefore, some of the oioi we monitored in three surveys over the 27 months since transplanting may have only just persisted or have been slowly dying because of inadequate rooting, especially in Lower quadrats. Others, and especially those in Upper levels may have established their roots sooner and therefore been able to grow new shoots spread out laterally, and flower.

5.3 Will competition with other plants prevent ongoing oioi growth?

Our monitoring over the 27 months since transplanting identified higher survival, healthier leaves, more leaf elongation, more new leaves, more lateral spread, and more flowering in oioi planted in the Upper level. A spade-width divot was cut in this sward around each oioi when planted. This will have relieved them from competition with the rank sward for a short period before grass grew back to surround and potentially smother the oioi. It might be that this grass sward initially protects the newly planted oioi by reducing wind and transpiration, and it clearly reduced risks of browsing by rabbits and hares. But will competition for space, light, rainfall and nutrients eventually stall oioi growth and spread, or even eliminate it altogether?

So far, oioi has been eliminated from only one of the 48 Upper quadrats with rank grass. Oioi leaves had overtopped the rank grass sward in a few quadrats and so will have at least partially alleviated their competition for light. In other cases, the oioi leaves were found lying prone under a thick mat of grass, from where recovery and propagation seems very unlikely. One close spaced Upper quadrat had a thick and merged canopy of oioi leaves that had completely excluded the grass between the original plants. This shows that eventual self-maintaining single-species stands of oioi are potentially achievable in the Upper zone. Nevertheless, the great majority of Upper quadrats had masses of grass growing in between them or overtopping them, and this raises a serious concern that most oioi will eventually be excluded by competition with grass.

We have initiated a follow up experiment to test this concern. A random selection of half the Upper quadrats were sprayed by a graminicide, Haloxyfop, on 28 April 2025[41]. Grass growth and any response of the oioi will now be monitored on the the sprayed and unsprayed quadrats over the next year to test whether (i) the grass sward is significantly reduced, (ii) oioi were damaged by the spray, and (iii) oioi survival, growth and spread were accelerated by selective elimination of grass.

Mākaka is clearly spreading through the 'Upper' zone around the high tidal zone. This spread on the eastern flank of South Arm has been accelerated by mass planting as part of the Tūmai Beach Restoration Trust's ecological restoration programme[42]. However, mākaka is also beginning to colonise the western margin of South Arm where there has been no deliberate planting so far. This shows rapid dispersal and natural regeneration via seed dispersal has been triggered. This raises the

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[41] This experiment was funded and authorised by the Otago Regional Council as an adjunct to their *Spartina* eradication programme in Otago estuaries (Haloxyfop was being used to kill Spartina immediately adjacent to the oioi quadrats).
[42] Tūmai Beach Environmental Enhancement Group (2024).

potential for eventual competition between oioi and mākaka – they may happily co-exist in close proximity, or one might exclude the other.

Three-square is also rapidly spreading within the terrestrial margin of the glasswort meadow of South Arm, and glasswort itself is gradually colonising the loose sediments left in wheel ruts and extending the marine margin of the salt meadow. It is unknown whether these changes will restrict or facilitate oioi establishment in the longer term.

5.4 Strategies for accelerating spread throughout Te Hakapupu

The *Tōitu Te Hakapupu* project team have planted around 375 oioi at two additional sites within the Te Hakapupu catchment[43]. Over 90% of 75 oioi planted in lower banks around sediment ponds on a farm appear to be surviving, but only about 60% of those planted around glasswort ponds within the ORC Estuary reserve (at the end of Wetlands Road) have survived. The thriving oioi at this latter site were planted along permanently wet seepage/drainage areas, whereas those that died were planted in "good marginal zone" between water and glasswort[44]. They may have succumbed to seasonal changes in size of the ponds within the glasswort meadow.

Other stands of oioi are not known in Te Hakapupu, so our collective establishment of under 2,000 oioi is a small beginning of potentially valuable biocultural restoration of an entire catchment.

Sediment trapping, reduction in water flow, bioremediation and biodiversity enhancement are all expected from successful establishment of oioi along waterways[45]. A test of 'Nature based solutions' to moderate water, sediment and nutrient flows and lessen the impact of floods on catchment health was recently launched by Otago Regional Council[46]. Further planting of oioi within South Arm and other parts of Te Hakapupu would contribute to the goals of this project. Prioritisation could require a trade-off between selection of sites where (i) flood protection is most needed, (ii) sedimentation and nutrient pollution risks are high, (ii) biodiversity and mahinga kai gains would be maximised (e.g. creation of inaka spawning sites), and (iii) the chance of successful and low maintenance establishment of oioi is most likely.

Only sites with permanent and secure exclusion of stock should be considered. Hare and rabbit control may also be needed if their browsing is severe. Oioi will provide excellent ecosystem benefits in both freshwater-terrestrial and saltwater-terrestrial ecotones. In saltwater ecotones and if a detailed map of saltwater levels and substrate elevation is not available, planting is more likely to succeed in patches with slightly raised ground, especially where grass growth is already naturally reduced by infrequent saltwater inundation. In freshwater-terrestrial ecotones, planting in depressions or slight hollows where freshwater seeps or occasionally pools is also likely to succeed. Planting where freshwater flows into estuaries would be particularly valuable, but planting the margins of such tributaries even well above tidal levels, would be potentially valuable provided that competition with introduced grass can be managed in the early stages of establishment. Preliminary results of our Haloxfop trial will be

[43] Melanie White, Email 31 March 2025, quoting field observations by Daniel van den Kerkoff.

[44] Daniel van den Kerkoff, *in litt*.

[45] Reviewed by Young *et al.* (2023).

[46] https://www.orc.govt.nz/environment/biodiversity/nature-based-solutions-study/

available next year. If initial signs are encouraging and follow-up spraying can be funded, a more definitive evaluation of the cost-effectiveness of continual applications of a graminicide for establishing a large and self-maintaining stand of pure oioi in critical seepage zones should be available after three years.

Low impact 'Chenier sills' can be constructed to dampen wave action to protect plantings, encourage the build-up of sediment and reduce shoreline erosion[47]. The west flank of the outer areas of South Arm would be a practical and useful site for testing their efficacy. Addition of fresh, unsalted soils behind the protecting rocks might aid initial establishment. Companion planting with other saltmarsh species that are more resilient to water currents and saltwater inundation and/or saline soils could help oioi establishment. The success and added cost of these strategies would best be assessed in a few critical sites for restoration identified by the trade-off's in catchment level benefits suggested above.

Measuring outcomes is more important than simply monitoring inputs, so the best indicators are linked to the highest ecosystem management goals of any restoration project. Ecosystem changes are often very slow to emerge and this research has emphasised how even the establishment of small numbers of oioi is slow and patchy. Long-term systematic monitoring will be needed, certainly well beyond the formal life of the *Toitū Te Hakapupu* initiative, to reliably gauge the collective effort and investment of so many people to improve ecosystem and community wellbeing.

6. Recommendations for oioi restoration

Our planting trial has reinforced all of the thirteen general recommendations emerging from our review of literature and the experience of oioi planters, as summarised on page 36 of Young *et al.* (2023).

More specific recommendations now include:

1. Escalate planting of oioi in South Arm, and elsewhere in Te Hakapupu. Establishment in South Arm has been successful, albeit patchy and slow.
2. There is no evidence of sexual reproduction adding to spread, and lateral spread by vegetative means has been slow (approximately 10-15 cm in 27 months since planting), so expect full restoration of ecosystem benefits in decades from now.
3. Bolster spread by planting adjacent to successful quadrats, especially in the inner and mid areas of South Arm.
4. Abandon all planting in loose estuarine sediments – eventual establishment of oioi in these areas will depend on pioneer colonisation by other species, potentially including glasswort, and the gradual build-up of raised substrates and/or reduction in seawater incursions.
5. Follow-up monitoring of all the oioi quadrats in three years – there are encouraging signs that *in situ* growth and spread is accelerating already, but more time and evidence is required to test whether oioi will eventually flourish in glasswort meadow. Only escalate planting of oioi into glasswort meadow if this follow up monitoring indicates eventual success is likely.

[47] See Figure 6 of Young *et al.* (2023).

6. In the interim target new planting on slightly raised ground near the terrestrial margin of glasswort meadow, especially in the vicinity of freshwater influx or pooling.
7. Investigate the cost and feasibility of testing Chenier sills, adding non-saline soils, and companion planting to enhance oioi establishment success.
8. Dig up a small sample of oioi from Upper and Lower levels to measure root mass and formation of lateral leaders. This will pinpoint whether the main ecological barrier to establishment in estuarine margins is mainly driven by soil salinity, or saltwater inundation, or both.
9. Monitor the fate of oioi in the terrestrial margin of the saltmarsh to test whether(i) rank grass naturally excludes oioi, and (ii) whether regular applications of a graminicide is a cost-effective method of establishing a self-maintaining single species stand of oioi.
10. If competition with grass can be overcome, establish a series of bridgehead stands of oioi around the upper edge of the glasswort meadow. Gradual lateral spread from a strongly growing bridgehead could eventually penetrate the glasswort meadow itself, whereas isolated planting directly into glasswort may struggle to establish and spread.
11. Oioi should be planted as close as practical together in areas where growth is expected to be slow and where competition with other plants is expected. Elsewhere and when the goal is to maximise areal spread, individual oioi plants can be planted even 1 m apart without compromising the chance of establishing. A strategy of planting several widely spaced clusters of closely packed oioi represents an intermediate strategy.
12. Stakeholders and experts should formulate a model for prioritising site selections for planting oioi (and companion plants) in Te Hakapupu that trades-off risks and benefits of (i) flood protection, (ii) sedimentation and nutrient pollution impacts, (iii) biodiversity gains, (iv) mahinga kai opportunities, and (v) the chance of faster, more successful, and lower maintenance dependent establishment of oioi. Permanent and effective exclusion of stock browsing is essential in these site selections.

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David Fletcher performed the statistical modelling and analysis.

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Appendix A: Model selections for oioi performance.

This table identifies significant predictors of Oioi success when all data are used compared to when zone C2 quadrats and any quadrats with more than half the oioi showing signs of browse have excluded from the modelling. The small number of 'Wet' quadrats placed in loose sediment were excluded altogether in these models.

Response variable	Data Filter	Main Effects			Interaction effects			
		Level	**Spacing**	**Area**	**Level x Spacing**	**Level x Area**	**Spacing x Area**	**Level x Spacing x Area**
Presence	All data	✓	✓	✓	✓	▪	▪	▪
	Without Browse or C2	✓	✓	✓	✓			
Browse	All data	✓	✓	✓	✓			
	Without Browse or C2	NA	NA	NA	NA			
Bright green leaves	All data	✓	▪	✓	▪	✓		
	Without Browse or C2	✓	▪	✓	▪	✓		
Grey leaves	All data	✓	▪	✓	▪	✓		
	Without Browse or C2	✓	▪	✓				
Dead	All data	✓	▪	✓	▪	✓		
	Without Browse or C2	✓	▪	✓	▪	✓		
Flowering	All data	✓	▪	✓	▪	✓		

	Without Browse or C2	✓	▪	✓	▪	✓		
Grass height	All data							
	Without Browse or C2							
Oioi leaf length	All data	✓	▪	✓	▪	✓		
	Without Browse or C2	✓	▪	✓	▪	✓		
Lateral spread	All data	✓	✓	✓	✓	✓		
	Without Browse or C2	✓	✓	✓	▪	✓		
New leaves	All data	✓	✓	✓	✓	✓	✓	✓
	Without Browse or C2	✓	✓	✓		✓		
Other vegetation cover	All data	✓	▪	✓	▪	✓		
	Without Browse or C2	✓						