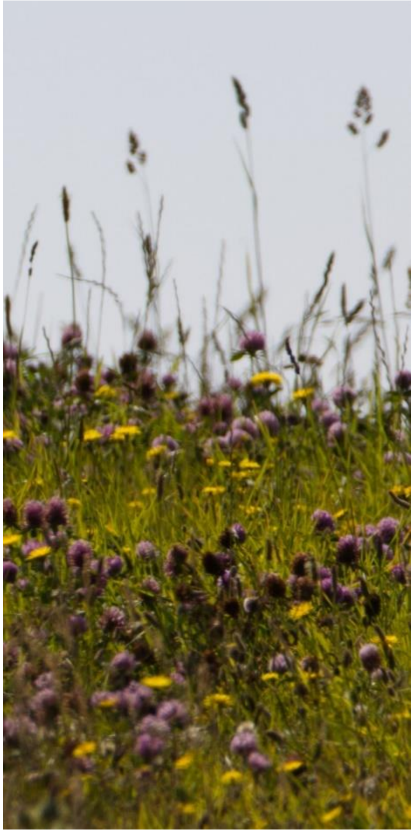
Oioi (jointed wire rush) planting experiments in Te Hakapupu

Experimental rationales and designs

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Executive Summary

The rationale, design, and methods of two experiments to test the constraints and opportunities for re-establishing oioi (Jointed wire rush, *Apodasmia [Leptocarpus] similis*) in a degraded arm of Te Hakapupu (Pleasant River) estuary are described in this report.

The main experiment compares survival, growth and spread of 1,664 oioi (i) planted in different elevations across the ecotone between estuarine and brackish habitats and adjoining abandoned pasture; and (ii) when planted 0.25 m, 0.5 m and 1 m apart. Quadrats of oioi planted at lower elevations in glasswort (*Sarcocornea quinqueflora*) beds are predicted to be stressed by more frequent and prolonged inundation by tidal flows and consequent hyper-saline soils. However they may also escape competition by introduced plants that cannot cope as well with the more saline conditions at lower elevations. Conversely, survival and spread of oioi planted just within the terrestrial zone (just above the glasswort delineation of the estuary edge) may suffer increased competition from weeds, especially introduced grasses. Closer spacing of plants may increase survival and growth by reducing competition, but also reduce the rate of spread of oioi. Our experiment is designed to measure these potential trade-offs to advise on the most cost-effective planting strategy to maximise establishment and rate of spread of oioi.

A second experiment tests whether seasoning of 80 nursery-grown oioi with different concentrations of seawater could enhance their ability to withstand sudden salt shock when first transplanted into hyper-saline soils. If so, restoration of oioi will be more cost effective and oioi might be planted in a much larger proportion of the degraded estuary sediments.

Survival, growth and spread of the experimental plantings will be monitored at six monthly intervals until winter 2025, when a report and recommendations for an adaptive management approach to re-establishing oioi in *Te Hakapupu* and other degraded estuaries will be published.

Biocultural restoration of oioi is important for improving ecosystem health (invertebrate, fish and bird habitat, cleansing water, binding carbon) and promoting community and cultural wellbeing.

Contents

1. Need for oioi planting trials at Te Hakapupu

The relatively unmodified saltmarshes in Aotearoa New Zealand have significant value in providing important habitat for indigenous invertebrates, fish, and birdlife. They provide important ecosystem services of sediment stabilisation, water purification and carbon sequestration. The ecosystem health of saltmarshes, and estuaries more generally, is often degraded. Sometimes these habitats are removed altogether for coastal development and farming.

This research is designed to assist a specific goal to restore oioi in 'South Arm' of Te Hakapupu (Pleasant River estuary), 5km northeast of Waikouaiti and 45 km north of Dunedin, South Island. 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].

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 2008 required reinstatement of tidal flows on South Arm[2] and ecological impact assessment and restoration plans suggested that oioi (Jointed wire rush, *Apodasmia [Leptocarpus] similis*) be planted around the newly reflooded areas[3]. 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[4].

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[5]. The project is jointly led by Kāti Huirapa Runaka ki Puketeraki and Otago Regional Council and is co-funded by the Ministry for Environment and Otago Regional Council. *Toitū Te Hakapupu* funded the establishment of the experiments described here.

A review of literature and restoration practice[6] emphasised that establishing oioi in new estuary areas can be relatively tricky. 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 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[7].

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[1] South-east Marine Protection Forum (2018).
[2] Dunedin City Council (2008).
[3] Wildlands Consultants (2007a,b,c).
[4] Tūmai Beach Environmental Enhancement Group (2021).
[5] 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).
[6] Young et al. (2023).
[7] Young et al. (2023).

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.

Oioi experiments

No replanting of the South Arm of Te Hakapupu has occurred before this experiment because it is expected that many of the saltmarsh species will naturally recolonise the area in time. However, oioi is an exception – it apparently spreads very slowly and predominantly by vegetative means, so there is a need to establish some 'bridgehead' stands from which local recruitment can naturally occur. 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 then, and was then driven extinct since by sheep and cattle browse and trampling[8]. There has been obvious spread of glasswort (*Sarcocornia quinqueflora*) 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.

Survival and spread of oioi in and around saltmarshes are variable and site specific. Identification of the restricted areas where it might succeed can be helped by surveys of water levels and inundation frequency and duration, but such surveys are expensive and complex, and usually well beyond the resources available to most saltmarsh restoration teams. Instead, planting is most often guided by following broad 'rules of thumb' and an adaptive management ('learning by doing'[9]) approach.

This report describes the rationale and study design of two experiments to guide potential future scaled-up oioi planting at Te Hakapupu in the coming decade. The first and main experiment tests spacing and site constraints on survival and spread of oioi; the second experiment tests whether nursery-grown oioi can be seasoned to better withstand salt shock before being planted into high-saline soils at Te Hakapupu.

Both experiments are being conducted to assist an 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[10].

[8] Grazing by cattle eliminated oioi from the margins of Northland dune lakes (Tanner 1992).
[9] Walters & Holling (1990).
[10] '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).

2. Experiment #1: habitat and plant spacing selections

2.1 Aims

Determine optimum habitat and plant spacing to maximise survival, growth, and spread of oioi at South Arm, Te Hakapupu.

2.2 Experimental rationale and design

A review of research and best practice by restoration managers from around Aotearoa New Zealand[11] identified habitat selection and plant spacing as key determinants of restoration success, but also emphasised how much oioi success was site specific for reasons they did not fully understand. Accordingly, we chose habitat and spacing as the two experimental variables in our main planting trial and spread the experimental treatments widely to test local constraints to reinstating oioi in South Arm of Te Hakapupu.

Altogether 1,664 Oioi were planted in 208 'quadrats', each with 8 plants (Figure 2 & 3, Table 1). Two habitat and three spacing treatments were combined in a balanced design to be able to test whether there was a significant interaction between habitat and spacing effects. 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.

Margins of estuary and glasswort beds were walked by Henrik Moller in December 2022 and recorded using two hand-held Garmin GPSs[12]. The location of each quadrat was estimated by GPS. Accuracy of between 3-5 m expected. Mapping was done using QGIS version 3.24 by Chris Garden.

Broadscale arrangement of quadrats between habitats, strata, and planting zones are shown in Figures 3 & 4. Examples of the detailed arrangements of quadrats within an estuary margin zone ('A') and within a brackish stream entering South Arm (zones 'G' and 'H') are shown in Figures 5 and 6 respectively[13]. The rationale and details for this design is now outlined below.

2.2.1 Habitat

Research and the experience of teams attempting to establish oioi in new areas has identified the importance of elevation within the estuarine-terrestrial ecotone and beneficial effects of freshwater flow or seepage that promote oioi survival and growth[14]. Spread deep into intertidal zone is limited primarily by inability to deal with hyper-saline soils and prolonged inundation with tidal flows, though it survives and grows better where freshwater dilutes the saltwater. Also, oioi might not compete effectively in some of these more fertile terrestrial and semi-aquatic sites in its establishment phases without active weed and pest management.

[11] Young et al. (2023).
[12] GPSmap 76CSx and GPSmap 64.
[13] Detailed maps of all the zones are held by Kāti Huirapa Plant Nursery and Henrik Moller for detailed follow-up in future monitoring.
[14] Young et al. (2023).

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* – McWilliams Stream stratum; Bottom, right – Wet quadrat in McWilliam Stream zone 'G'.

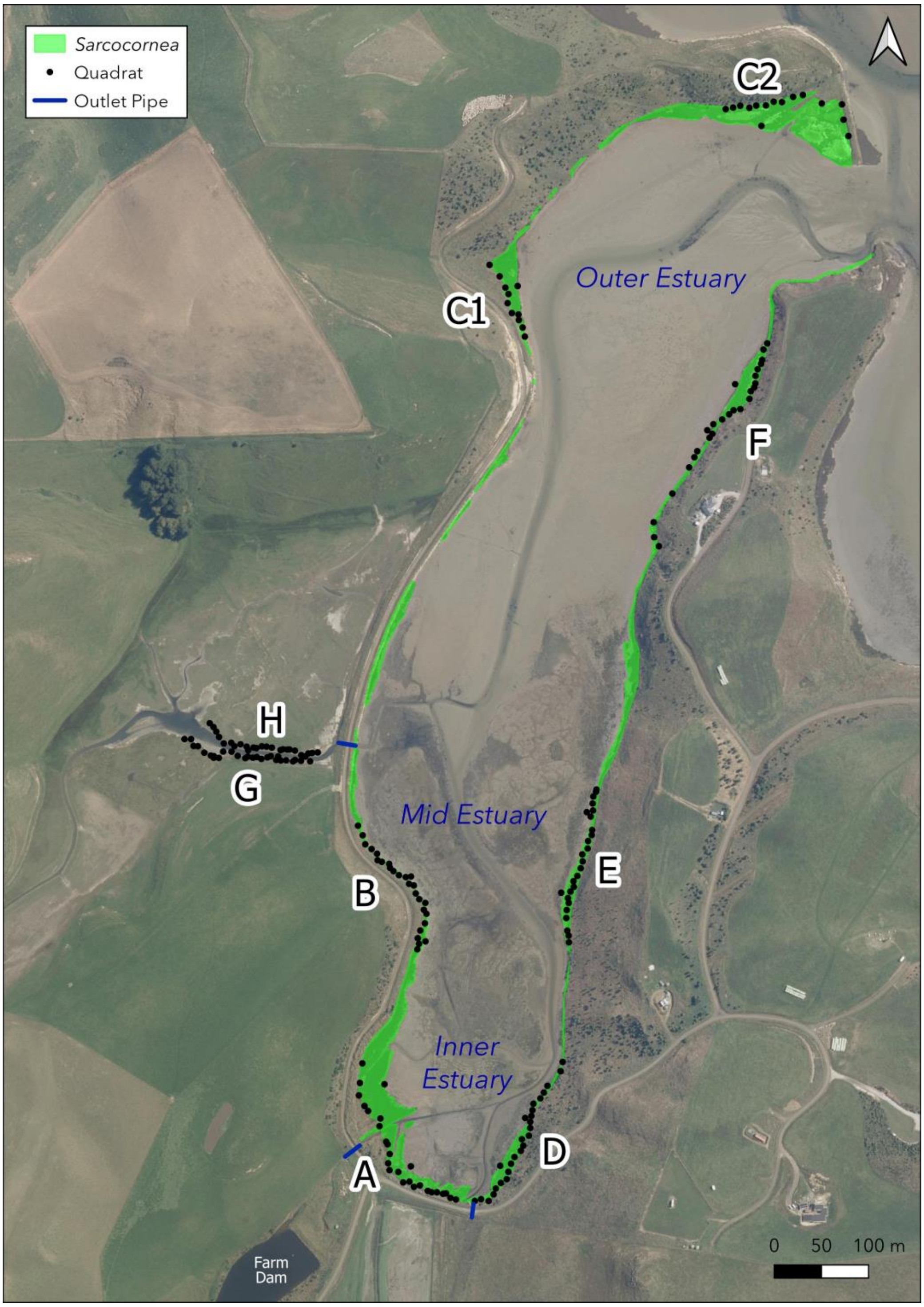

Figure 3: Arrangement of experimental oioi planting quadrats around South Arm, Te Hakapupu. Each quadrat received eight oioi plants, spread equally across eight zones (A-H). Two zones were placed along the margins of McWilliam Stream, and two zones in each of three strata ('Inner', 'Mid' and 'Outer'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

Table 1. Number of quadrats and number of plants [in square brackets] within each stratum and treatment for Experiment #1.

Stratum	Zone	Treatment (Habitat/Level-Spacing)							All treatments
		Upper-0.25m	Upper-0.5m	Upper-1m	Lower-0.25m	Lower-0.5m	Lower-1m	Wet	
Inner Estuary	A	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
	D	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
Mid Estuary	B	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
	E	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
Outer Estuary	C1	1 [8]	2 [16]	2 [16]	0 [0]	2 [16]	2 [16]	1 [8]	11 [88]
	C2	3 [24]	2 [16]	2 [16]	4 [32]	2 [16]	2 [16]	1 [8]	15 [120]
	F	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
McWilliam Stream	G	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
	H	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	4 [32]	2 [16]	26 [208]
All Strata & Zones		32 [256]	32 [256]	32 [256]	32 [256]	32 [256]	32 [256]	16 [128]	208 [1,664]

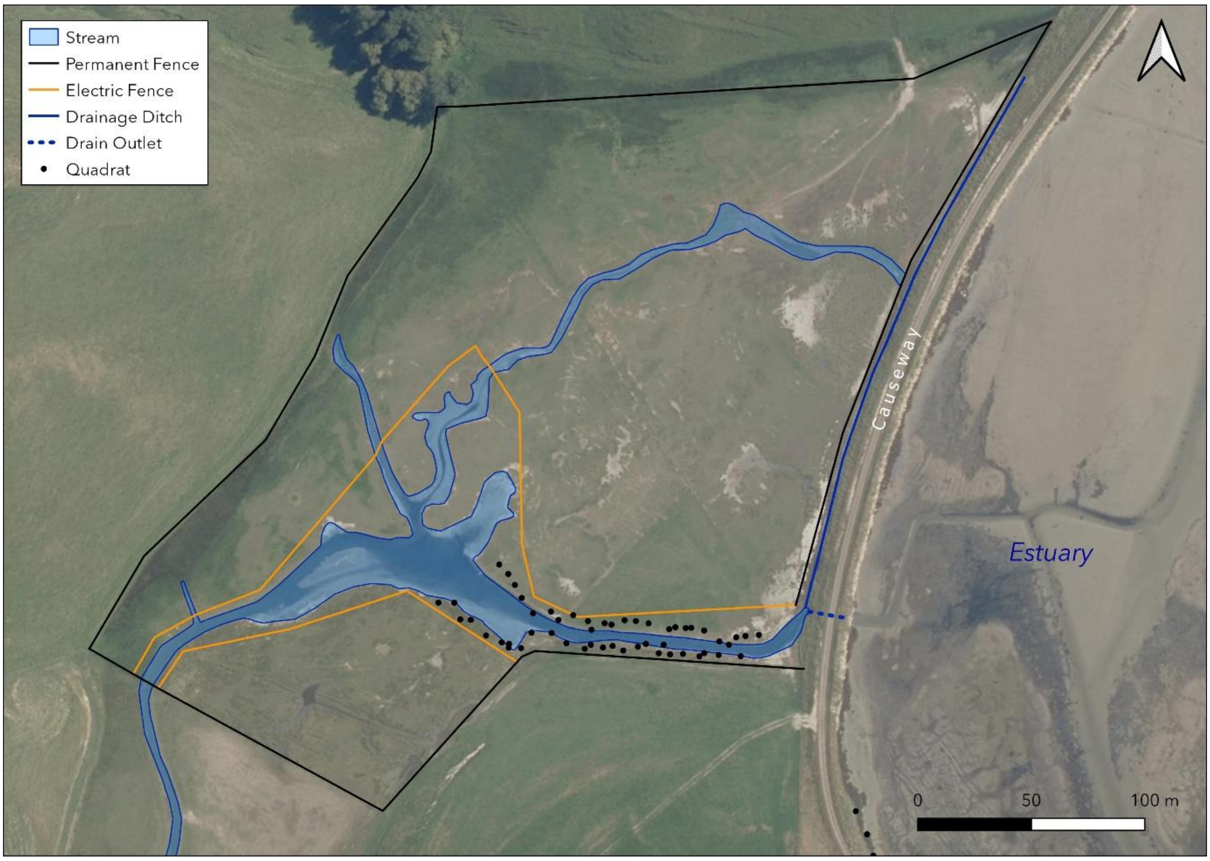

Figure 4. Arrangement of the oioi experimental planting quadrats within the 'Mc William Stream' area, Te Hakapupu. The deep blue areas always have water flowing from a stream flowing off the neighbouring farm. The light blue areas often have standing water when weather has been wet. Water often stands on 0.65 hectares within the entire paddock of 2.7 hectares. The surrounding pasture areas also flood after heavy rain, so the oioi that we planted along the stream margin are sometimes inundated with fresh water. The orange and black lines denote fences erected to exclude sheep and cattle from the planting area and 2.05 of pasture. The drainage pipe running under the causeway has a hinged flap that allows freshwater to flow into the estuary after heavy rain and prevents most saltwater from flowing back from the estuary into the lower stream area. Stunted pasture growth, bare ground and presence of small quantities of glasswort along the margins of the stream indicate that some saltwater occasionally reaches the western-most extent of the oioi quadrats, but the habitat can be characterised as being mainly freshwater but mildly brackish.

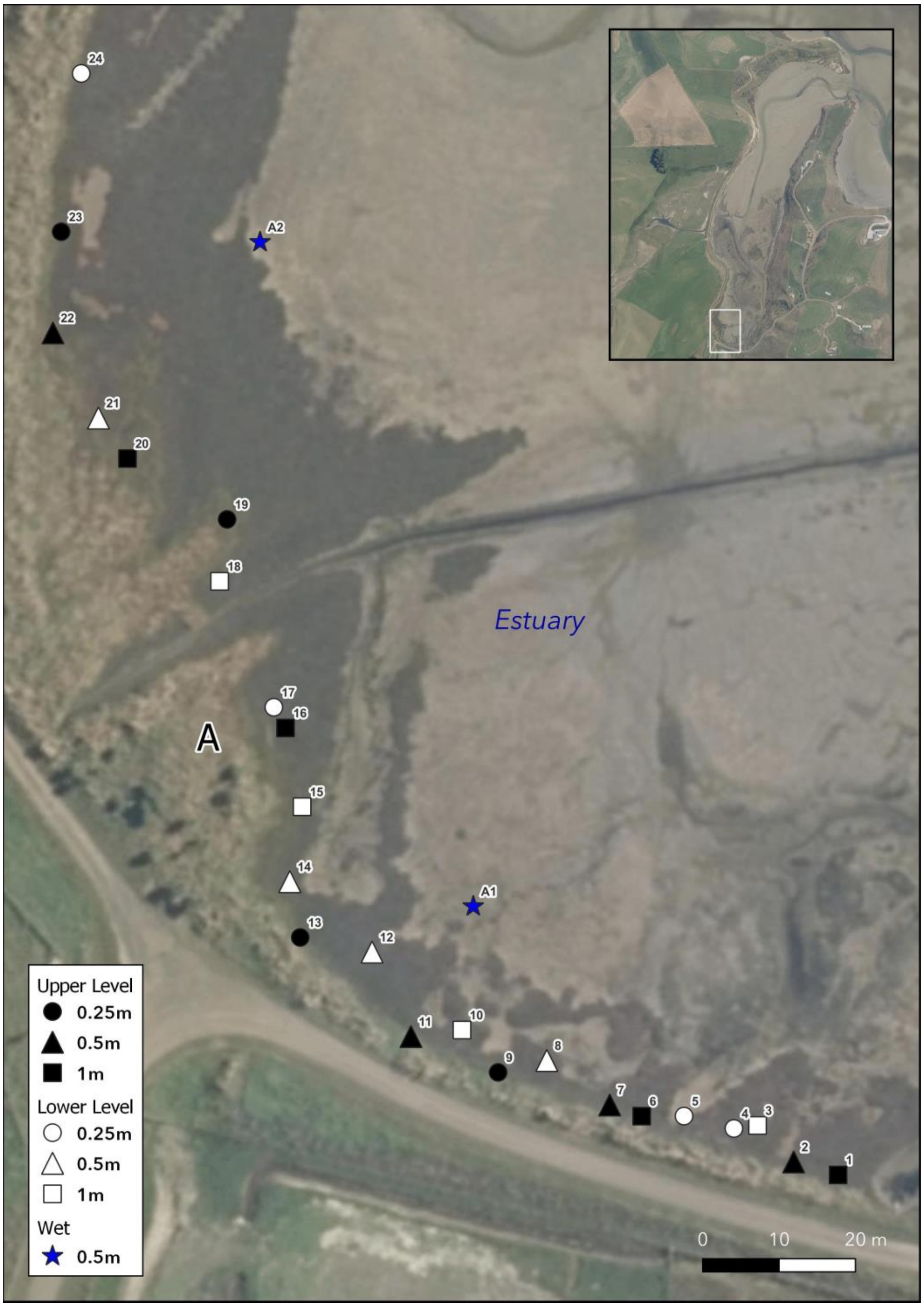

Figure 5. Arrangement of the oioi experimental planting quadrats within Zone A of South Arm, Te Hakapupu. Darker grey areas are glasswort beds. 'Upper' quadrats (black symbols) were placed with their lowest margin on the edge of the glasswort limit; 'Lower' quadrats (white symbols) were placed 2 m below the glasswort limit (Figure 7). Equal numbers withing each habitat treatment had plants 0.25 m (circles), 0.5 m (triangles), or 1 m (squares) apart. 'Wet' quadrats (Stars) were planted further into the estuary beyond the glasswort beds. Quadrats were allocated randomly between treatments at randomly chosen distances between 5 and 9 m apart along the estuary margin.

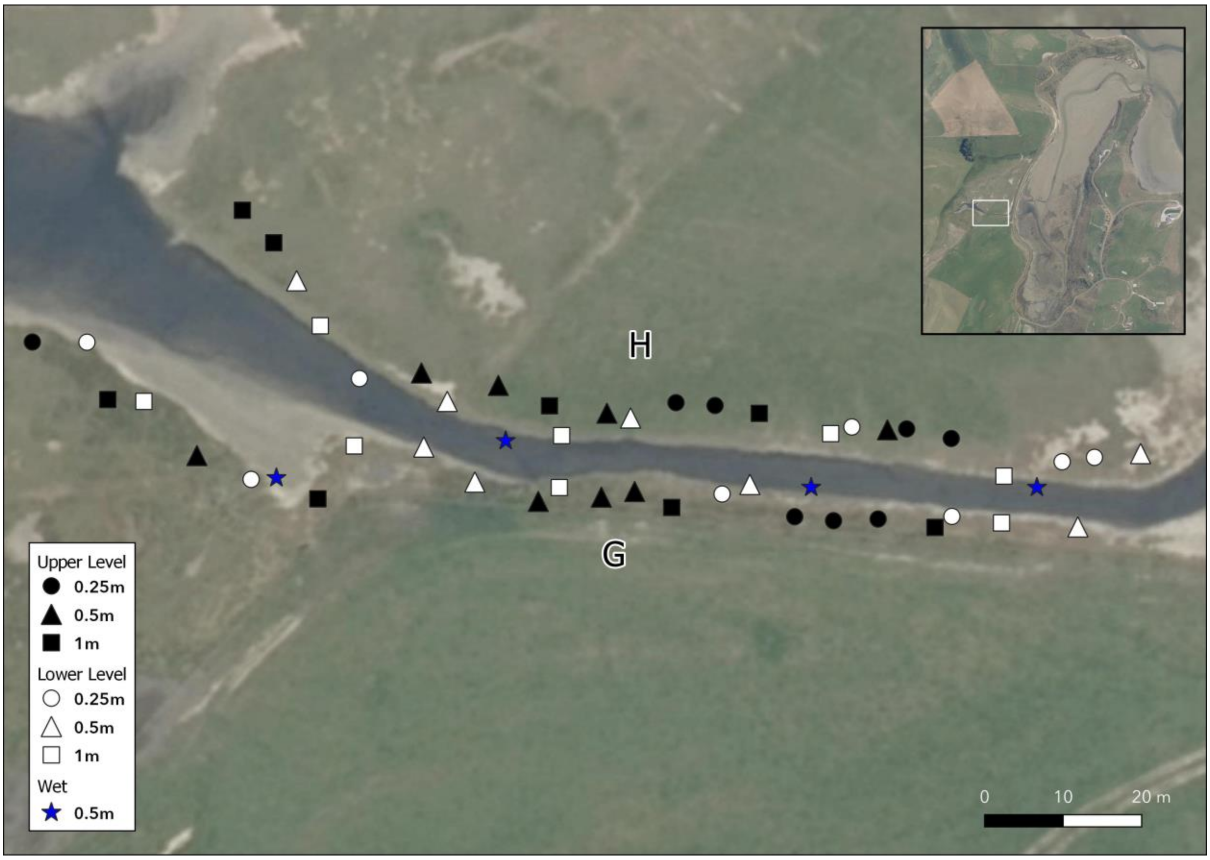

Figure 6. Arrangement of the oioi experimental planting quadrats within Zones G & H of the 'McWilliam Stream' area, Te Hakapupu. Here the lip of the stream edge was used to position the 'Lower' quadrats (those most frequently flooded) and 'Upper' quadrats were position 2 m away from the lip of the stream. 'Wet' quadrats (Stars) were planted within the main streambed and were always sitting in water (Figure 8).

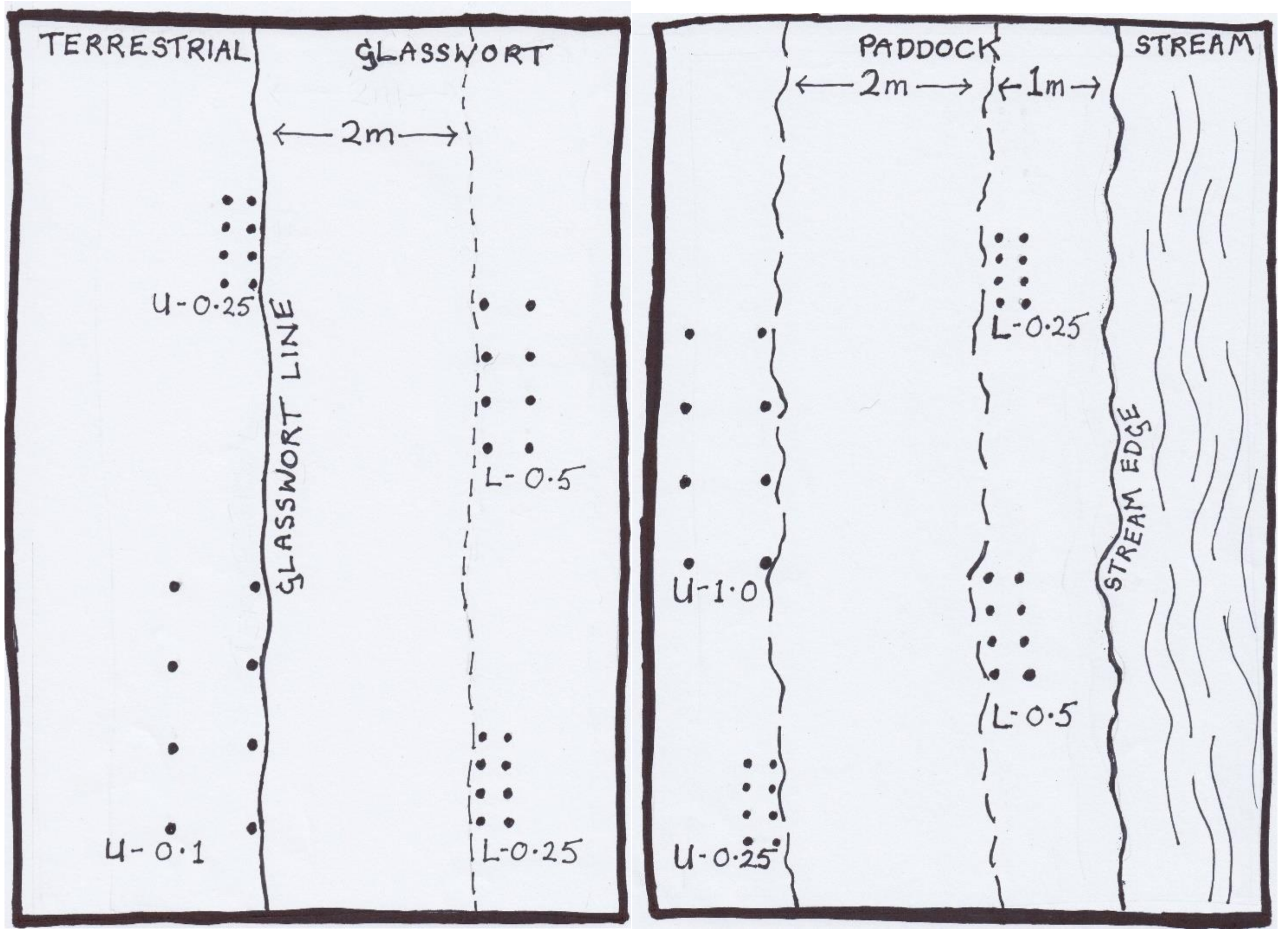

Figure 7. Layout of oioi quadrats along the South Arm estuary margin (left) and McWilliam Stream edge (right). There were 8 plants in each quadrat (shown as dots in the diagrams), planted either 0.25, 0.5 or 1 m apart. 'Lower' quadrats were at lower elevations and subject to more water or stream flow than 'Upper' ('U'). Quadrats were positioned randomly along the estuary or stream edge line.

Oioi experiments

Establishment of oioi in South Arm is particularly challenging. Some of the margins of South Arm are flanked by rocks or steep clay banks, especially along a newly formed causeway on its western flank that was inserted in 2009 when the Tūmai farm park subdivision was consented and the estuary's tidal flows were reinstated. Rank pasture grasses growing down to the estuary edge threaten to smother oioi. These grasses are naturally excluded from the estuary bed itself by the saltwater, but glasswort is rapidly and naturally colonising by spreading outwards from the estuary edge[15]. It is unknown whether glasswort will compete with and so block establishment of the oioi planted within it, or whether the soils around the margin of South Arm will prevent oioi from growing vigorously and spreading amongst the glasswort.

Therefore, we targeted our experimental planting mainly on a very narrow zone along the margins of the restoring estuary. We used the 'inland' glasswort distribution limit as the critical delimiter of estuary-terrestrial ecotone boundary. We had sufficient plants to test two contrasting habitat/elevation zones, so half the South Arm quadrats were position along this glasswort line (designated as the 'Upper' treatment), and half were placed 2m below the glasswort line ("Lower" treatments) as detailed in Figure 7.

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 neep 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 oose, especially close to the main water flow channels (Figure 2).

Seven oioi were planted in these loose sediment sites where they were regularly covered by tidal flows of Te Hakapupu's South Arm in autumn 2022. This was intended as a preliminary trial to see if planting beyond the glasswort beds flanking the estuary might succeed. The oioi turned brown and grey, and shoots became brittle within the first year. However small green shoots were visible by November when we were about to establish the experiments described here, and the plants remain intact. We do not yet know if they will survive and eventually prosper. If they do, there is considerable scope for spreading oioi throughout much of South Arm, but many of the inferences from research and restoration teams suggest that this is perhaps unlikely. We decided to test this by placing a relatively small number of quadrats much deeper down the estuary sediment elevation and beyond where glasswort currently has reached. Two 'wet' quadrats, each with 8 plants, were placed in each zone to test this opportunity – their locations are shown as stars in Figures 5 and 6, and an example is photographed in Figure 2.

In view of the challenges presented by South Arm for oioi restoration, it was decided to test establishment success in the lower margins of one of the two main streams that flow into South Arm (Figure 2)[16]. Including zones G and H in the 'McWilliam Stream' habitat will test the review's prediction that survival and growth will be relatively high there compared to in the estuary margins. Adding a brackish habitat component to the experiment also spread risk of wasting all the time and funds should oioi not flourish in South Arm at all. But most importantly, oioi helps trap sediment and strips

[15] Our GIS estimates the total area of glasswort beds in December 2022 to have been 2.1 hectares. The entire estuary area within South Arm is estimated to be 27.4 hectares.

[16] A third stream enters but first discharges into a farm pond that has been dammed to allow extraction of water for the Tūmai Beach farm park subdivision. Occasionally after prolonged rain, the dam overflows and discharges freshwater into South Arm at about the middle of Zone A.

nutrients and pollutants from the water running off the farm and otherwise entering Te Hakapupu. Planting oioi along the edge of freshwater inflows therefore contributes directly to the aims of the Toitū Te Hakapupu and Tūmai Beach Restoration projects. Andrew and Sara McWilliam fenced and removed stock from 2.1 hectare of paddock around the margins of approximately 400m of stream to enable the oioi restoration and later planting of other species (Figure 4).

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 8). Two quadrats were placed out in the main stream bed in each of the two McWilliam Stream zones i.e. equivalents to the same 'wet' quadrats and also shown as stars in Figure 6.

2.2.2 Plant spacing

Our initial literature and restoration practice review revealed wide variation in spacing distances when planting oioi. Some teams 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[17]. Spacing was most commonly around 0.5 and 0.7 m, but occasionally was only 0.25 m, or as wide as 2m. We had sufficient plants for just three treatments, so settled on 0.25, 0.5 and 1m spacings for the primary experiment and balanced the number of quadrats evenly between these three treatments.

Saltmarsh and wetland restoration teams planted oioi closely within clusters as described above, but then spread clusters throughout the landscape, occasionally along transect lines that traversed key gradients (commonly tidal flows and elevation along the saltmarsh ecotone). Spacing clusters wide apart maximises learning and spreads the risk of failure. One team targeted the head of their estuaries to minimise risk of tidal flows disrupting planting beds, but generally teams did not take dispersal of propagules or landscape considerations into account when deciding on the layout of the planting. Accordingly, we arranged 156 experimental quadrats within the South Arm itself, with equal numbers within three strata: the 'Inner', 'Middle' and 'Outer' zones of the estuary (Figure 3).

2.2.3 Random placement of quadrats and balancing treatments

Sites for quadrats were arrayed randomly within each strata 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 an elevation/spacing treatment to each site until all treatments were balanced. Occasionally a site had to be skipped because it fell on a rocky section of shoreline, in which case we simply stepped on till the next suitable planting site was found.

[17] 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).

2.2.4 Plant propagation and planting

Oioi used in these experiments were sourced from Matai Nurseries, Waimate, in 2021. They were split and re-potted in January 2022, and then grown on at Kāti Huirapa Runaka Plant Nursery until used in these experiments 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. They 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.

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 between 24 and 27 November 2022[20]. Divots were cut to a spade width (ca. 160 mm) and depth (ca. 200 mm) in the substrate. 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.

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

3. Experiment #2: seasoning plants for salt shock protection

3.1 Aim

Test whether prior irrigation of oioi with seawater enhances their survival, growth and lateral spread when planted into estuary sediments.

3.2 Experimental rationale

Comparison of performance of the 'Wet', 'Lower' and 'Upper' quadrats with oioi planted 0.5m apart in Experiment #1 will eventually test where prolonged establishment in the more saline substrates could ever be achieved. If adequate survival and growth occurs in the softer open areas South Arm, much larger areas would become available for oioi restoration to enhance ecosystem services for Te Hakapupu.

Whatever the long term prospects for plants inserted into bare and hyper-saline estuarine substrates, it is clear that oioi suffer an initial shock when first transplanted. It seemed unlikely that inundation by water itself impairs survival or growth because oioi do very well in freshwater inundations. This led us to hypothesise that salt shock impairs survival, plant growth, root health and vegetative reproduction by lateral extension of rhizomes[21].

We wondered if the impact of initial salt shock could be overcome by seasoning the plants with diluted seawater before they are transplanted into these more exposed areas of South Arm.

3.3 Design and methods

We retained a random selection of 80 oioi from the same stock as used for Experiment #1 to test the salt shock hypothesis.

Five groups, each of 16 plants within their original PB3 planter bags, were sat in five separate plastic trays inside three wooden crates at Tūmai Beach farm park (Figure 8). Trays were irrigated in five treatments:

- Undiluted seawater[22]
- 75% seawater, 25% rainwater[23]
- 50% seawater, 50% rainwater
- 25% seawater, 75% rainwater
- 100% rainwater.

The plastic planter bags have holes cut in their sides to allow water into the roots, and trays were kept topped up to a level just below the top of each bag. The experimental plants were therefore sitting in a water bath and constantly saturated. The wooden crate was needed to exclude browsing by rabbits and to prevent wind from blowing over the plants within their water bath.

[21] Field and nursery transplant experiments in Otago concluded that salinity in the soils was likely to be the main block to oioi performance (Partridge & Wilson 1988).

[22] Seawater was collected from Karitāne Beach, some 10 km south of the mouth of Te Hakapupu. Collection of water well away from nearer rivermouths was advised to reduce any risk of introducing *Bonnemaisonia hamifera* a red algae weed to Hakapupu.

[23] Collected from the roof of a house at Tūmai Beach farm park.

Figure 8. Pretreatment of oioi plants for a seawater irrigation experiment at Te Hakapupu. Eighty bagged oioi were sat in five water-baths with different concentrations of seawater and within three wooden sided crates (Upper). Scoring the number and size of roots protruding through irrigation holes in the planter bags was part of monitoring the plants' responses to seawater treatments (lower). Roots were scored as 'small', 'medium' and 'large/matted' as shown from left to right.

Oioi experiments

The experiment was established in January 2023, and water replaced at every 4 to 6 weeks. The position of individual plants within each tray was rearranged, and the position of the five trays within the wooden crates was rotated at each refresh of the water treatment in order to eliminate any differences in light and exposure between treatments.

Changes in oioi survival, leaf colour, seed formation, and root protrusion through the holes in the planter bags was scored at regular intervals.

The plants will be transplanted in August 2023 into soft sediment in areas without glasswort that are frequently inundated with tidal flows in South Arm. Two quadrats from each treatment will be randomly positioned at least 10 m apart. Each quadrat will have 8 oioi spaced at 0.5 m apart. This middle spacing was chosen to match that used for 'wet' quadrats in Experiment #1 and thereby maximise the comparison of seasoned and unseasoned transplants in the long term.

Survival, colour, growth, seeding and vegetative reproduction of the oioi within and near each of the 10 experimental quadrats will be monitored at 6 monthly intervals until winter 2025 to test whether seasoning plants by seawater irrigation can mitigate the effects of salt shock and enhance establishment prospects when planted into hyper-saline substrates at Te Hakapupu.

4. General discussion & predictions of outcomes

Successful establishment of oioi in South Arm of Te Hakapupu cannot be guaranteed. The adaptive management experiments described here are designed to test preliminary expectations before deciding whether and how to scale-up planting of oioi elsewhere in South Arm, in other places within Te Hakapupu, and potentially in other estuaries around Aotearoa. Learning will be fastest if adaptive management experimental treatments test extremes of potential treatments or site conditions, while still concentrating most of their investment on places or strategies that seem most likely to succeed from current knowledge[24].

A review of research and best practice by restoration managers from around Aotearoa New Zealand concluded that oioi struggled to establish in loose and highly saline substrates at lower elevations within the estuarine-terrestrial ecotone.[25] Nevertheless, vigorous and intact stands of oioi are seen well out from the estuary edge at Merton, approximately 7 km from our Te Hakapupu study site. Also, preliminary test transplants of seven oioi plants into soft and bare substrates within Te Hakapupu in Autumn 2022 gave mixed signals[26]. The plants turned grey and brown and their leaves became brittle in the ensuing month, but they did survive and there was sign of green shoots emerging from the base of the plants in the following summer. Perhaps survival and growth in such soft sediments is impaired but not precluded? If initial establishment succeeds, perhaps the resilience of the stand mitigates the harsh conditions by building its own substrate of interlocked roots? Or more simply, establishment in these extreme challenging substrates will be impossible and the persistence observed in the preliminary test is more a testament to the resilience of the original transplanted specimens which will now wither and die without reproducing.

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 and scared substrate (Figure 2). If it can eventually be colonised by oioi, ecosystem services provided by the plants can be greatly enhanced. In the meantime, the 128 plants within 'Wet' quadrats in Experiment #1, and the 80 oioi about to be planted out for Experiment #2, are at high risk of dying and therefore being wasted. However, placing 12% (208 of the overall 1744 plants) at high risk was considered acceptable in view of the benefit of testing habitat limits and a potential method of blunting effects of salt shock when oioi are first planted into estuarine conditions. Starting small and failing fast are ways to reduce overall risk and achieve long-term goals faster and more cost-effectively.

Our review of literature and restoration practice suggests that oioi are most likely to succeed where freshwater dilutes seawater influences. We therefore predict that survival, growth and spread of oioi will be greater in the McWilliam Stream zones ('G' and 'H') than in the South Arm estuary. The design criteria between estuary and stream could not be matched precisely (compare Figures 8 & 9). Predictions of relative changes in performance between treatments <u>within</u> each stratum are more reliable than predictions of absolute differences in survival, growth and spread <u>between</u> strata. Also, there are three sites where freshwater periodically flows into South Arm (Figure 3), so we will monitor whether oioi performs better in those vicinities. Other than such freshwater influences we have no *a*

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[24] Walters & Hilling (1990).
[25] Young et al. (2023).
[26] These surfaces are shown in the top row of Figure 2.

priori reasons for predicting differences in oioi outcomes between the 'Inner', 'Mid' and 'Outer' strata of South Arm.

Quantification of success indicators is now needed before lessons emerge and sound recommendations for future planting are possible. Annual mid-winter monitoring of the oioi plants will be undertaken until mid-2025 and preliminary recommendations formulated for the end of the *Toitū Te Hakapupu* project.

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. Long-term systematic monitoring will be needed, perhaps 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. A suite of biocultural restoration indicators are being developed by the *Toitū Te Hakapupu* project and community of 'citizen scientists' living in the catchment. At the very least, our oioi restoration project team hopes to be able to report successful re-establishment and natural expansion of oioi in a significant and currently degraded arm of Te Hakapupu. Our review of literature and expert knowledge that helped design the experiments described here makes us confident that re-establishment of flourishing oioi stands will trigger improved invertebrate, fish, bird, water quality outcomes. These ecosystem health gains will in turn lead to improved community and cultural wellbeing.

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