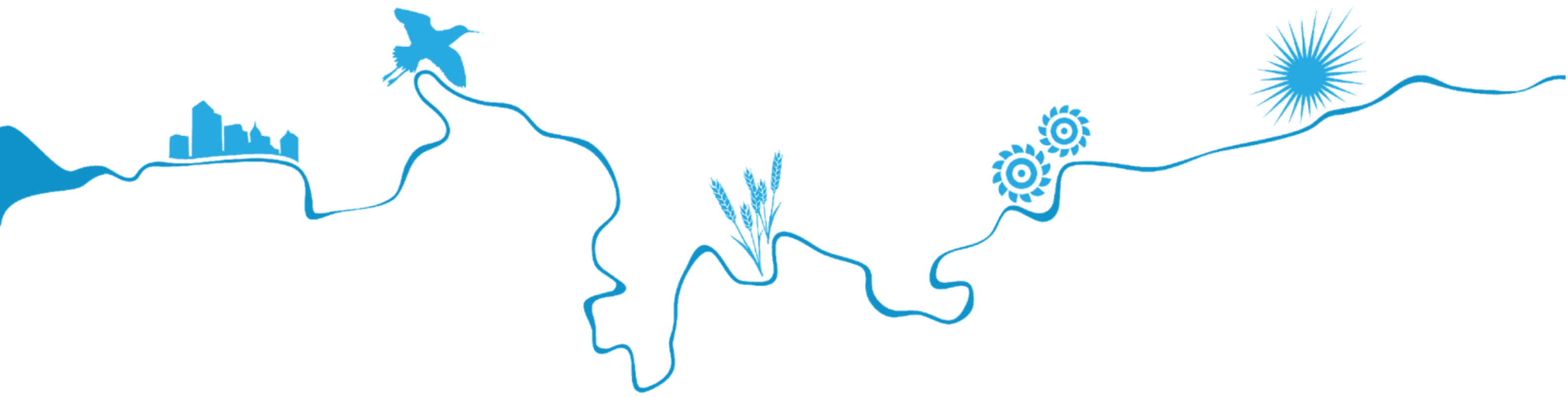
A restoration strategy for the Ruppia Community of the southern Coorong

Michelle Waycott and Ryan Lewis



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Enquires should be addressed to: Goyder Institute for Water Research
The University of Adelaide (Manager)
209A, Level 2 Darling Building, North Terrace,
Adelaide, SA 5000
tel: (08) 8313 5020
e-mail: enquiries@goyderinstitute.org

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Respect and reconciliation

Aboriginal people are the First Peoples and Nations of South Australia. The Coorong, connected waters and surrounding lands have sustained unique First Nations cultures since time immemorial.

The Goyder Institute for Water Research acknowledges the range of First Nations' rights, interests and obligations for the Coorong and connected waterways and the cultural connections that exist between Ngarrindjeri Nations and First Nations of the South East peoples across the region and seeks to support their equitable engagement.

Aboriginal peoples' spiritual, social, cultural and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages and laws which are of ongoing importance.

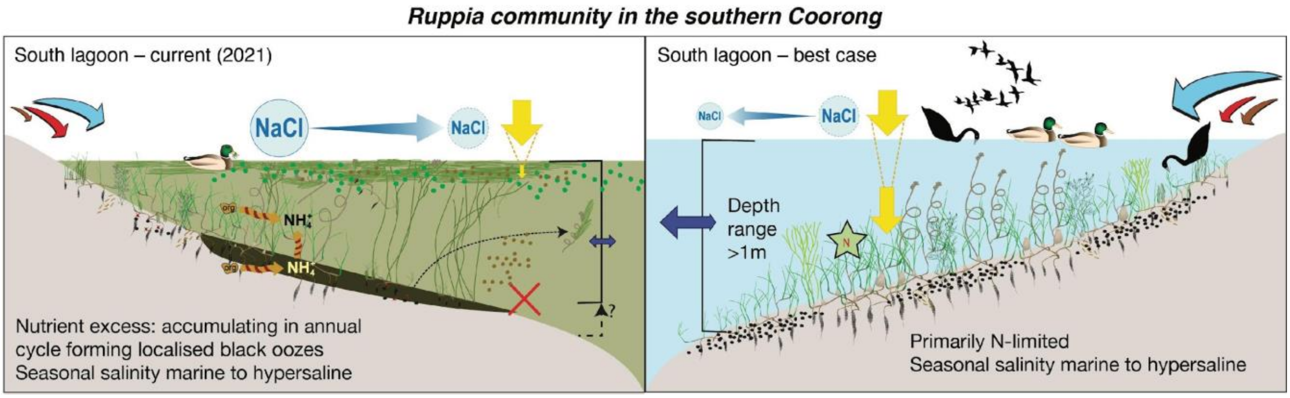
Executive summary

The Healthy Coorong, Healthy Basin program aims to improve ecological health of the Coorong and is committed to delivering outcomes that can be supported by an evidence base and adoption pathway such as this strategy describes. The goal of this strategy is to support ongoing management of the aquatic macrophyte community, the Ruppia Community, in the southern Coorong through evaluating restoration options. This technical report is structured as a stand-alone document, containing; an introduction and background to the southern Coorong and its aquatic macrophyte community and a review of restoration approaches in other systems where submerged aquatic macrophyte communities were impacted (Chapter 1); a case study from previous Coorong Ruppia Community restoration activities that provides context and insights that inform the restoration strategy (Chapter 2); and a detailed strategy for decision-making and management of future restoration activities (Chapters 3 & 4).

The restoration objective is to restore a resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions. Presented as a cycle enabling adaptable delivery, the strategy establishes options to identify pathways to support restoring the natural values and ecological functions essential for healthy and productive aquatic macrophyte populations. The application of the strategy is bespoke to the exceptional and unique environment of the Coorong, in particular the southern Coorong, however it could be applied elsewhere. No equivalent indigenous reference system for the Coorong is available for developing targets, therefore the way the Coorong ecosystem is currently managed is based on the Ramsar Management Plan and other associated policy documents.

The submerged aquatic macrophyte community of the Coorong is highly adapted to an annual cycle in water level and salinity, and longer-term changes in climate conditions that lead to even greater extremes in water level and salinity. Several species occur in this community, predominantly *Ruppia tuberosa* with *Althenia cylindrocarpa* and an unknown cryptic species of *Ruppia* detected through DNA screening. *Ruppia tuberosa* is dominant in the current Ruppia Community and has a very broad, or euryhaline, range of salinities that it grows in, and a complex life history with three pathways for surviving the annual hydrological cycles – seed production (annual adult die off, seed banks replenished, dominant strategy), turion production (annual persistence of vegetative propagule) or vegetative persistence (must remain covered by water).

Significant impacts which resulted from the Millennium Drought (2001–2010) are still being observed today. The Coorong South Lagoon experienced severe salinities of more than 150 g L^{-1} in summers from 2007 until the end of the drought in 2010 (for reference, ocean salinity is typically ~35 g L^{-1}). The ability of aquatic macrophytes to complete their life cycle was effectively lost during the 2001–2010 period and this led to the depletion of seed banks resulting in large-scale losses. Extreme environmental conditions (including high nutrients and salinity) caused by inadequate flushing flows, has led to the southern Coorong becoming hyper-eutrophic, which has impacted the Ruppia Community, leading to poor condition. Despite this, the Ruppia Community has slowly increased in extent to occupy the majority of potential habitat across the southern Coorong over the past 10 years. The biota of the southern Coorong has become dominated by fast growing primary producers, including phytoplankton and filamentous algae that are able to rapidly utilise the hyper-eutrophic conditions more efficiently than the Ruppia Community (figure below, left panel).

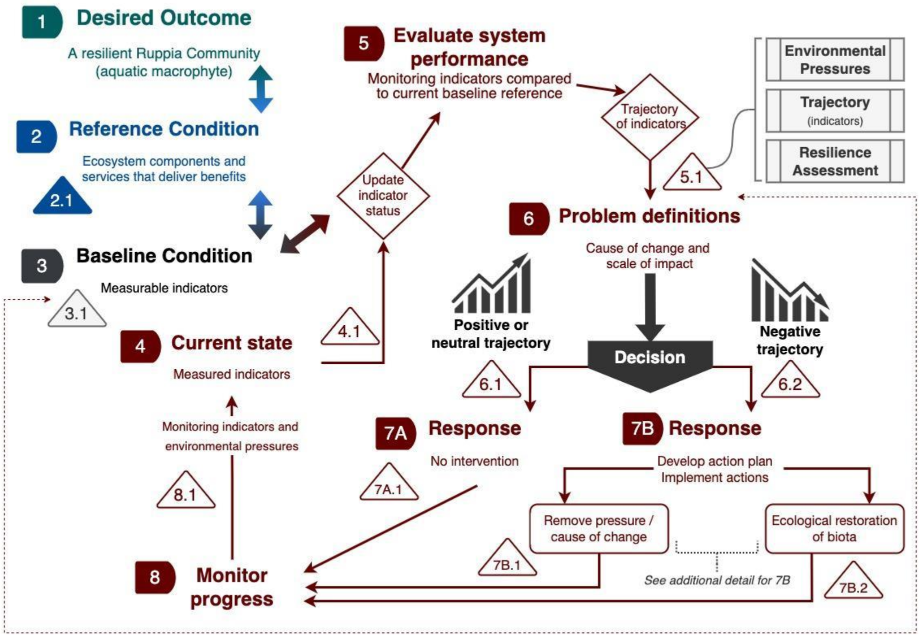


In the period immediately following the end of the drought, intervention to restore the Ruppia Community was implemented in the form of seed based translocations at five locations in the Coorong South Lagoon. The aim of translocation actions were to kick start recovery of the Ruppia Community across a wider range of locations. From 2012–2014, sediments densely laden with seeds were distributed from a donor site, Lake Cantara, about 15 km south of the Coorong, to the five translocation sites. A total area of 59 ha was treated with more than 700 tonnes of sediment containing an estimated 400 million seeds. At each site, sediments were distributed across different water depths, based on local site elevation.

Translocation sites were monitored for two years following intervention and found local colonisation of the Ruppia Community, and plant densities to increase annually. No further monitoring was undertaken at these sites until this study when sites were resurveyed along with nearby areas of similar conditions as comparators for locations without translocations. These observations, eight years later, demonstrated that compared to reference non-translocated sites, there was a significant improvement in biomass, seed bank and the number of turions produced at translocation sites. The donor site, sampled later in the year in spring, exhibited incomplete recovery from seed extraction 8-9 years ago. Unexpectedly, donor site seed banks were absent in winter unlike the Coorong sites, likely due to seasonal conditions favouring turion production. In summer, significant differences between donor and non-donor areas were detected, few seeds were observed in the seed bank of the donor site area and moderate seed banks were found in the non-donor areas. High numbers of turions were observed, with significantly more in donor sites. Note that interpreting the results needs to be done in context of the temporal variation in environmental conditions experienced across the site. For example, La Niña summer weather cycles in 2020-21 and 2021-22 have led to longer-term availability of water entering the Coorong system and directly affected the growing season of plants.

Future restoration strategies should include monitoring prior to, during and post implementation for a minimum of 10 years following actions of the scale undertaken in the 2012–2014. The lack of ongoing monitoring at the translocation sites prevents inferences on whether this intervention contributed to system wide expansion of the Ruppia Community, currently the extent is equivalent to that pre-drought. Clearly, there were positive benefits from the translocation, although it remains uncertain if these actions had an impact more widely.

A workflow to implement the Restoration Strategy (schematic of process below) has been developed recognising there are a range of scales, temporal and spatial at which disturbance can occur, including; 1. acute perturbation, 2. cumulative impacts, 3. inter-annual climate cycle, 4. climate change, 5. management action change with examples elucidated for the southern Coorong. The stages in the cycle have also been informed by international examples and standards that have become widely adopted as best practice. Already available policies provide a starting point and have been applied to developing a new resilience evaluation framework for the Ruppia Community of the Coorong to interpret results from monitoring activities. Planning for ecological restoration in the Coorong should be adaptable to the environmental complexities, the history of change and potential for future change within the system. A proposed expanded strategic monitoring framework is developed that includes four classes of indicators; A. environmental pressures, B. indicator trends (positive, primarily biological), C. indicator trends (negative, biological, chemical) and D. Resilience. These are then applied to a restoration progress assessment tool for the translocation activities post Millennium Drought and the current program to reverse long-term environmental pressures.



This process identified a number of knowledge gaps; habitat links, genetic connectivity, landscape connectivity, pollution, and invasive or harmful species. This workflow could be developed as the basis for an evidence-based monitoring program that could inform ongoing management of the Coorong ecosystem. Monitoring data would apply to the provision of inputs to decision support tools such as the Coorong Dynamics Model and its Ruppia Habitat Suitability Index. The workflow enables feedbacks through revisiting the baseline condition regularly.

Ultimately the application of the Restoration Strategy represents the need to decide if intervention is required at all, and if so what type of restoration is needed. Utilising this decision framework, robust ecological knowledge and modelling, will enable outcomes to be tested and allow us to predict the outcomes of proposed interventions with confidence.

Acknowledgments

This project is part of the South Australian Government's Healthy Coorong, Healthy Basin Program, which is jointly funded by the Australian and South Australian governments.

Historical and complementary data used in this report were funded by The Living Murray (TLM), a joint initiative funded by the New South Wales, Victorian, South Australian and Commonwealth governments, coordinated by the Murray–Darling Basin Authority. Data sets associated with The Living Murray initiative are cited by author and date in the text, they may be flagged by referring to the abbreviation for this program, TLM.

The research team, including our individual researchers from The University of Adelaide, South Australian Research and Development Institute, Flinders University and the Department for Environment and Water wish to thank the members of the Ngarrindjeri community gratefully and respectfully for their support of this research. In particular, we recognise and value the knowledge of Ngarrindjeri community members shared with this program, that has come from the connection that has been maintained by community to the lands and waters of the region and individual experiences.

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1 General introduction

1.1 Background

The Coorong is a long, narrow lagoon (Figure 1) at the end of the River Murray stretching for more than 100 kilometres parallel to the coast south of the Murray Mouth (Figure 2). The main body of the lagoon is separated from the ocean by a narrow sand dune system, the Younghusband Peninsula. The Murray Mouth has a history of being ephemerally closed and today ocean connectivity is maintained through a dredging program during periods of low flow (Mosley et al. 2018). The Coorong is a culturally, environmentally and economically important wetland at local, national and international scales. Notably the Coorong and Lakes Alexandrina and Albert Wetland was recognised in 1985 as a wetland of international importance under the Ramsar Convention. Long-term declines in the flow of water from the River Murray have led to reduced system connectivity, lower water levels, and reduced flushing of nutrients and salt out of the Coorong (Brookes et al. 2018). These impacts were exacerbated during the Millennium Drought (2001 to 2010), the worst drought and one of the driest periods ever recorded across south-eastern Australia (Ferguson et al. 2013, Van Dijk et al. 2013). During the Millennium Drought the combination of low flows and high evaporation led to low water levels and extreme high salinity in the southern Coorong (Figure 3A); defined here as the section of the Coorong from Long Point in the North Lagoon to south of Salt Creek at Tea Tree Crossing (Figure 1).

Figure 1. View of the central section of the Coorong, South Australia, during January 2021. The photo looks northward from Swan Island at the southern end in the foreground towards the very narrow flow constriction at Parnka Point at the centre of the region, shown by the visible string of small Islands ~8 km away (top of photo). The ocean is visible to the left separated from the Coorong by the Younghusband Peninsula. Note the opaque, yellow coloured water, caused by water column phytoplankton blooms. Image provided by Geoff Gallasch, used with permission. Refer to Figure 2 for additional details on locations.

The Millennium Drought contributed to significant declines in the abundance and distribution of many native plants and animals (Paton 2010) (Figure 3B). Severe salinities and low water levels limited the ability of aquatic macrophytes to complete their life cycle (Figure 3C) resulting in large-scale losses of the Coorong aquatic macrophyte community dominated by *Ruppia tuberosa* (Rogers and Paton 2009, Paton and Bailey 2010, Whipp 2010, Paton et al. 2011, Department of Environment Water and Natural Resources 2014b, Collier et al. 2017, Department for Environment and Water 2020b). A reduction in food web complexity also occurred and continues to persist in the southern Coorong. The biota is currently dominated by fast growing primary producers, including phytoplankton and filamentous algae, having greater capacity to utilise the hyper-eutrophic conditions than the Ruppia Community (Paton 2010, Mosley and Hipsey 2019, Department for Environment and Water 2021c) (Figure 1).

The State of the Southern Coorong discussion paper, updated in June 2021, described the current state of the southern Coorong system as degraded, and in a persistently hyper-saline (>60 g L^{-1}) and hyper-eutrophic state with low connectivity and low food web complexity (Department for Environment and Water 2021c). The hyper-eutrophic state encourages the growth of problematic filamentous, planktonic and benthic algal blooms. These blooms inhibit the growth (reduced light availability) and reproduction (interfering with reproductive structures and effective seed set) of aquatic macrophytes, which exhibit poor condition and resilience (Collier et al. 2017, Paton et al. 2017b, Mosley et al. 2020, Paton et al. 2021, Lewis et al. 2022). As a result, fast turnover biota such as micro and filamentous algae have come to dominate nutrient cycling processes (Mosley et al. 2020, Priestley et al. 2022). Recent analyses determined that more than 50% of the water column nutrients originate in the sediments and around 90% of these are present as organic nutrients (Priestley et al. 2022). The State of the Southern Coorong discussion paper proposes returning the system to a mesotrophic (i.e. not excessive or low nutrient concentrations resulting in clear water with areas of submerged aquatic plants and medium levels of nutrients) state, where nutrient concentrations are lower and nutrient cycling involves longer-lived biota (Department for Environment and Water 2021c). Under mesotrophic conditions, nutrients would be incorporated into persistent seagrasses or other persistent higher biomass aquatic macrophytes and macroinvertebrates, and the fish and waterbirds that consume them.

Without intervention, conditions in the southern Coorong are expected to continue to decline, with persistent extreme hypersalinity and ongoing nutrient retention (Department for Environment and Water 2021c). These environmental conditions would be exacerbated by continued poor connectivity and compounded by reduced water availability under climate change (Department for Environment and Water 2021c). The Coorong Infrastructure Investigations Project (CIIP) of the Healthy Coorong, Healthy Basin program continues to investigate ways of improving ecological health in the southern Coorong including dramatic improvements to significant ongoing causes of impact on the biota, poor water and sediment quality (e.g. Mosley et al. 2020). Restoration enhancing activities are also proposed to augment the desirable outcomes of critical ecological functions under improved water management (Department for Environment and Water 2021c).

Actions to improve the ecological health of the Coorong and Lakes Alexandrina and Albert Ramsar Wetland will continue to be investigated with the long-term goal of reinstating critical ecological functions and restoring the southern Coorong to its *desired state* (Department for Environment and Water 2022d). Re-establishing a healthy aquatic macrophyte community such as the Ruppia Community (Lewis et al. 2022) is a critical component of any long-term strategy to achieve this outcome. The Restoration Strategy proposed includes ready-to-go options to guide management decisions and actions, to assist the aquatic macrophyte community build resilience and recover from varying severities of environmental stress and/or disturbance.

1.2 Aims

This investigation aims to improve our ability to undertake effective ecological restoration of the Coorong Ruppia Community by providing options that follow best practice guidelines and incorporate knowledge and experience of the Coorong ecosystem. We also identify knowledge gaps and recommendations for implementation using an approach that in principle could be applied to other biota of the southern Coorong.

This technical report presents the results of the Healthy Coorong, Healthy Basin program, Component 2 – Plants and Algae investigations completed during the period from July 2020 to June 2022. The Restoration Strategy presented incorporates existing policies and guidelines for seagrass restoration applicable in the Coorong and new strategies based on new knowledge generated through the Healthy Coorong, Healthy Basin program, including an assessment of the previous *Ruppia tuberosa* restoration actions in the Coorong South Lagoon from 2012–2014.

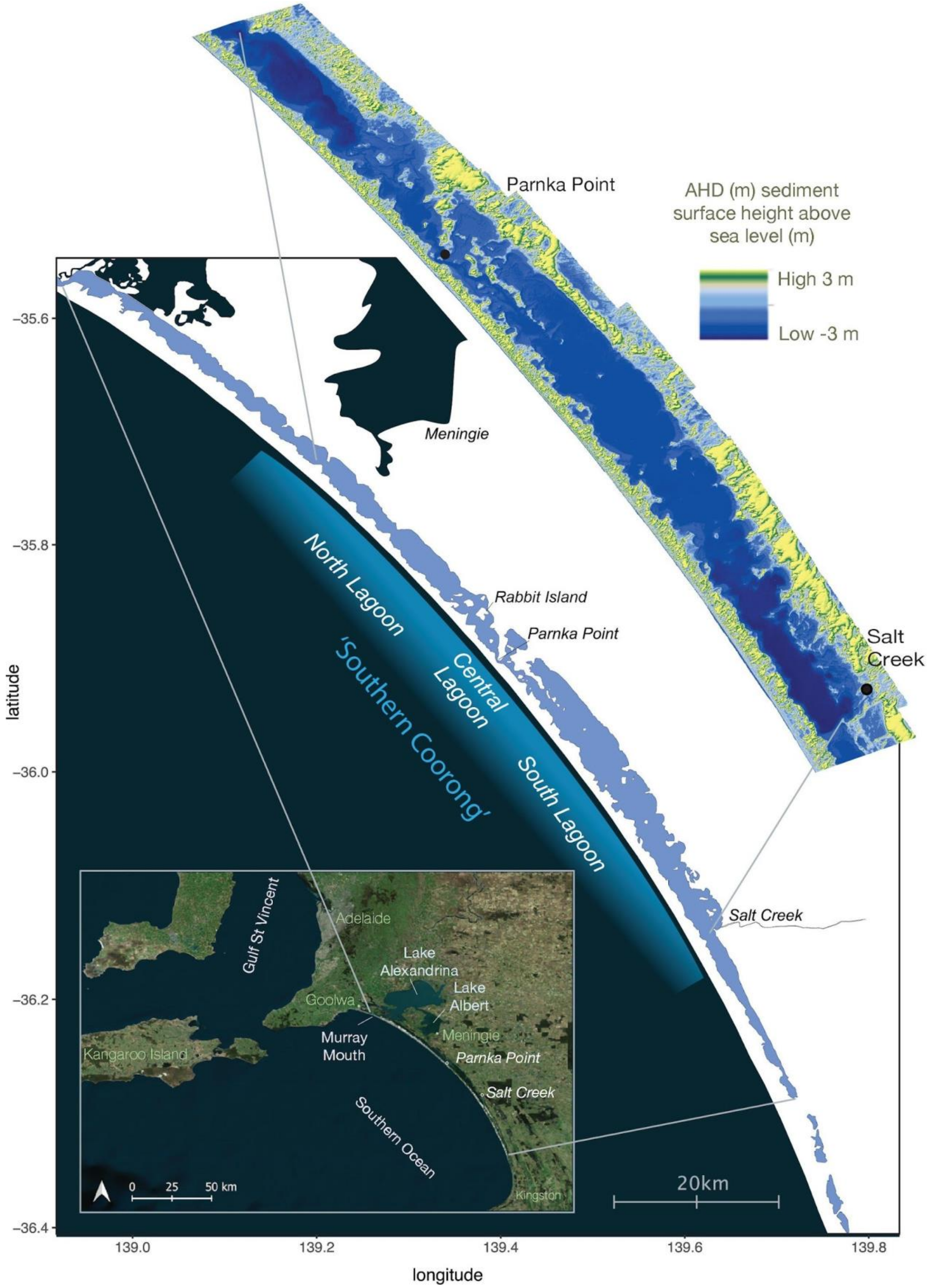

Figure 2. Main map and inset, the region of South Australia where the Coorong occurs showing key sites and landmarks. Top panel, colourised depiction of the sediment surface digital elevation model rectified to the Australian Height Datum (AHD, m) (Hobbs et al. 2019); darker blue deeper water, yellow and green dry land.

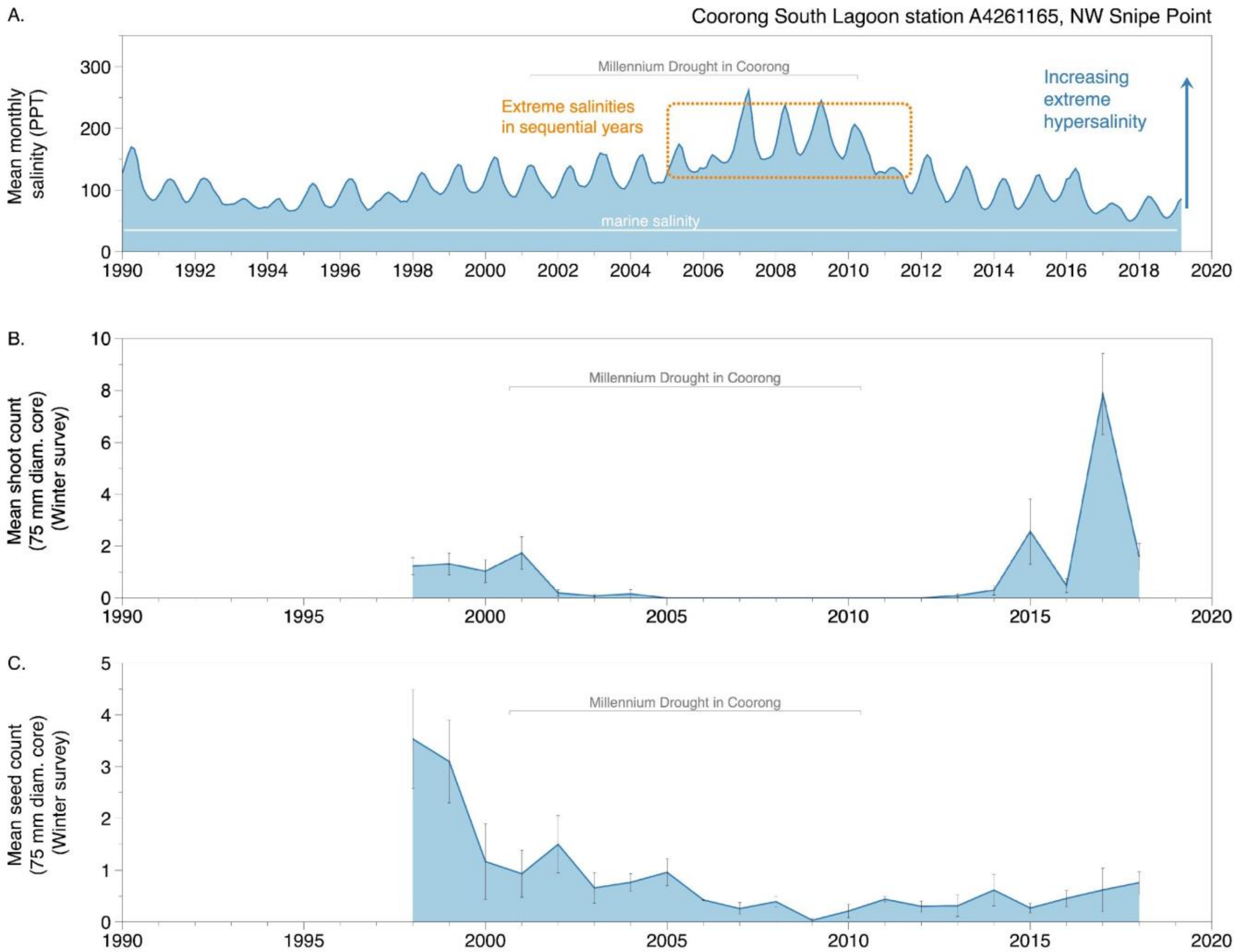

Figure 3. A. Mean monthly salinity (g L[-1]) based on data collected by the Healthy Coorong, Healthy Basin program's water quality monitoring project (Healthy Coorong Healthy Basin 2022b). B. Mean (± s.e.) shoot counts of *Ruppia tuberosa* (the Ruppia Community) per 75 mm diameter core in winter at Coorong South Lagoon sites south of Hack Point during The Living Murray program (Healthy Coorong Healthy Basin 2022c). C. As for B., but for abundance of seeds per core.

1.3 The 'Ruppia Community' in the Coorong

The extant aquatic macrophyte community of the southern Coorong is predominantly comprised of *Ruppia tuberosa* with *Althenia cylindrocarpa* also common (Nicol 2005, Collier et al. 2017, Paton et al. 2020, Waycott et al. 2020a). This aquatic macrophyte community has been defined as the 'Ruppia Community' by Lewis et al. (2022) and represents the contemporary assemblage. *Ruppia tuberosa* has been well documented as the dominant species since the 1970s, likely due to prevailing conditions of higher salinities and less frequent, high volume, freshwater pulses (Whipp 2010, Asanopoulos and Waycott 2020, Lewis et al. 2022). *Ruppia megacarpa* previously had a significant presence in the southern Coorong, including in the main lagoon, which can be verified from herbarium vouchers collected in the 1960s to 1980s from the Coorong South Lagoon (avh.ala.org.au; AD98004388, AD96624054, AD 96624060). *Ruppia megacarpa* was found to be present in waters adjacent to the extremely hypersaline Coorong South Lagoon during observations and surveys between 2020 and 2022 (Lewis et al. 2022). Another previously documented important component of the aquatic macrophyte community not detected in recent surveys was the charophyte *Lamprothamnium papulosum* that had an overt presence in the Coorong benthic macrophyte community in the past (Delroy 1974, Paton et al. 2015b, Lewis et al. 2022). Recognition of the changes in the aquatic macrophyte community composition in the Coorong has been determined through comparisons of direct observations since the 1960s (Noye 1973, Womersley 1975, Geddes and Butler 1984, Geddes 1987) and also inferred from biogeochemical analysis (Krull et al. 2008, Tibby et al. 2020). In particular, water levels and salinity regimes of the Coorong have become modified since the 1950s, as River Murray water has been restricted through managed barrage water releases that have led to changes in the timing and magnitude of water availability (Krull et al. 2008). As a consequence, the aquatic macrophyte community has had to adapt to lower water levels and higher salinities, and seasonal variation in both water level and salinity. The additional pressures of long-term climate cycles, particularly drought, have led to a community of aquatic macrophytes becoming highly resilient to the unique suite of prevailing conditions present in the system (Department of Environment Water and Natural Resources 2014b, Asanopoulos and Waycott 2020). Despite the presence of this highly resilient community of aquatic plants, they continue to exhibit slow recovery trajectories and poor resilience (Figure 3).

Under current management, the annual capacity for growth of the Ruppia Community remains at least in part dependent on River Murray inflows that are controlled by barrage operations (Paton et al. 2015b, Collier et al. 2017). Surveys from 2020 to 2022 as part of the Healthy Coorong, Healthy Basin program found the Ruppia Community to be distributed between the elevations of +0.5 m to -0.8 m Australian Height Datum (AHD) (Figure 4). Plants persisting in the +0.5 m to -0.8 m AHD elevation band had 0 to 0.6 m of water cover at the time of sampling (Lewis et al. 2022). The greatest proportion of sites (>95%) with plants present were in the depth range of ±0.25 m AHD (Figure 4) representing the shallow mudflats that are ecologically important for plants, macroinvertebrates and waterbirds. If water levels in the southern Coorong drop too early in spring then plants can become exposed leading to desiccation and inability to complete the reproductive cycle (Collier et al. 2017, Paton et al. 2017b, 2020) (Figure 5). If the lifecycle of the plants is disrupted over several consecutive years then seed banks can become depleted as observed during the Millennium Drought (2001-2010) (Paton et al. 2015b).

Distinguishing aquatic macrophytes species in the Ruppia Community of the southern Coorong is difficult when plants are non-reproductive due to very similar vegetative growth of species present, meaning that they are virtually indistinguishable from each other unless reproductive structures are present (Asanopoulos and Waycott 2020). Lewis et al. (2022) applied eDNA techniques to determine species level community composition of aquatic macrophytes that co-occur in the southern Coorong. These analyses documented a low diversity but multi-species assemblage that included *Ruppia tuberosa* along with two other co-occurring species, *Althenia cylindrocarpa* and an unresolved, potentially new, species of *Ruppia*. Lewis et al. (2022) also documented the common occurrence of *Ruppia megacarpa* seeds across the southern Coorong during their baseline surveys. Adult plants of *Ruppia megacarpa* were observed to be common in waterbodies adjacent to or that flow into the Coorong, such as Salt Creek and Mundoo Channel, however not common within the lagoons of the Coorong (Lewis et al. 2022).

The Ruppia Community has been typically referred to as *Ruppia tuberosa* in earlier data sets and published records (e.g. Phillips and Muller 2006, Paton 2010, Paton et al. 2015b, Nicol et al. 2018, Paton et al. 2021). It is considered a biological keystone 'species' in the Coorong supporting a number of critical ecological functions within the southern Coorong (Phillips and Muller 2006, Paton et al. 2015b). The Ruppia Community contributes ecological services by influencing water quality, stabilising sediments and providing habitat and food source for invertebrates, fish and birds (Rogers and Paton 2009, Paton et al. 2015b, Paton et al. 2016a, Brookes et al. 2018). The aquatic macrophytes that comprise the Ruppia Community are colonising functional forms and are characterised by having fast shoot turnover and a relatively short lifecycle (Kilminster et al. 2015). Lewis et al. (2022) observed longer-lived, perennial populations year-round. The persistence of perennial populations is likely dependent on inter-annual maintenance of sufficient water levels and moderate salinity. However, as has been well documented (Paton and Bailey 2010, Paton et al. 2015b, Paton et al. 2020), the majority of populations are currently dependent on a persistent seed bank and vegetative reproductive structures (turions) (Brock 1982) that enable them to survive through periods of low water or unsuitable environmental conditions (Kilminster et al. 2015, Asanopoulos and Waycott 2020). Given the current distribution of the Ruppia Community across the southern Coorong, species that co-exist are tolerant of hyper-saline conditions which have persisted since the Millennium Drought (Paton et al. 2020, Lewis et al. 2022).

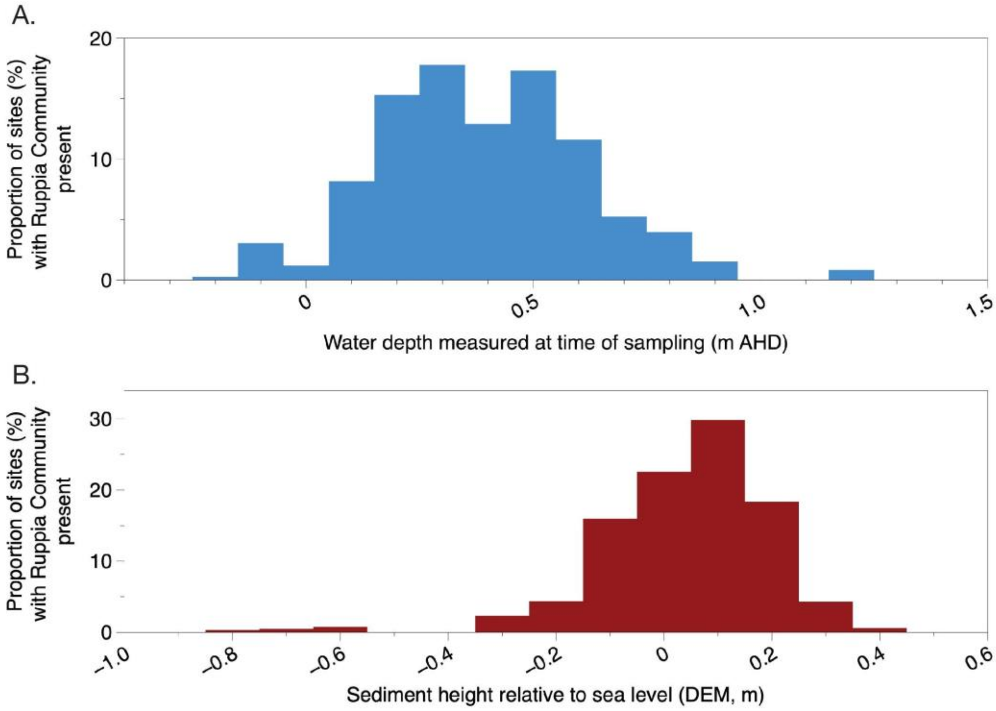

Figure 4. The proportion of sites (n=90) across the central and southern Coorong that had a Ruppia Community present (i.e. living plants present) during the reproductive surveys in 2020 and 2021 (Lewis et al. 2022); A. grouped by the in-field water height measured above the sediment at time of sampling calibrated to Australian Height Datum (AHD) and B. grouped by Hobbs et al. (2019) digital elevation model (DEM) sediment height above sea level (m AHD). Results for both measures of depth binned into 0.1 m intervals.

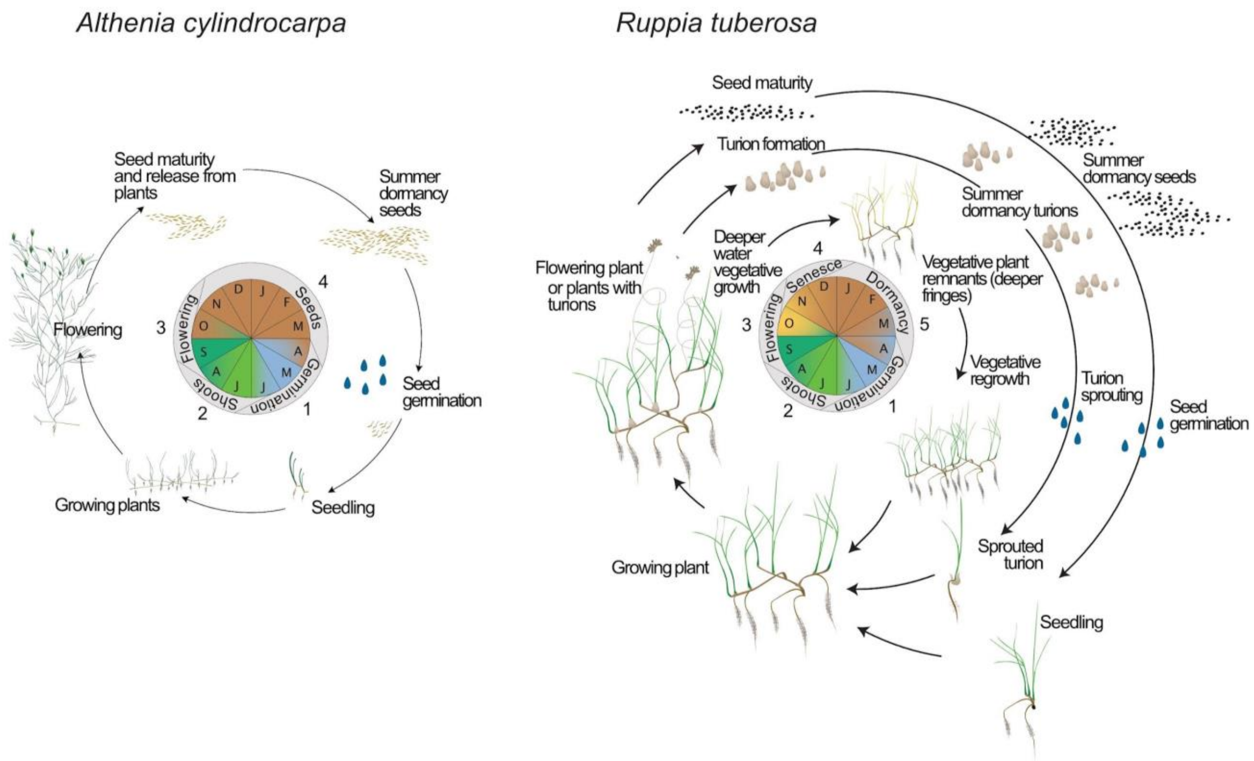

Figure 5. Summary schematic of the lifecycles for *Althenia cylindrocarpa* and *Ruppia tuberosa* depicting seasonal changes in the stages of growth, reproduction and senescence and broad timing of each life stage. Attribution: Michelle Waycott, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons.

In 1999, prior to the Millennium Drought, shoot counts of 7,000 m^{-2} were observed for the Ruppia Community, in contrast post-drought (2010) plants were completely absent at surveyed Coorong South Lagoon sites (Paton et al. 2011, Collier et al. 2017) (Figure 3). Currently, the Ruppia Community is widespread across the central and southern Coorong (Figure 7) and exceeds its documented pre-drought extent of occupancy (Paton et al. 2021, Lewis et al. 2022). Environmental conditions during this study included two La Niña years in a row contributing to freshwater inflows that maintained water levels within the preferred range for growth of the Ruppia Community. These preferable environmental conditions led to an expansion in the extent of occurrence of the Ruppia Community and populations at certain locations dramatically improved in condition. For example, in late 2021 an extent of occurrence of more than 52 km and mean shoot count m^{-2} of 21,546 was observed (Lewis et al. 2022), highlighting the continued post drought recovery trajectory of the Ruppia Community. It is likely that, in addition to the environmental conditions limiting recovery processes since the end of the drought, local scale dispersal and recruitment have been important factors in recovery of the Ruppia Community (e.g. Kendrick et al. 2012, Reynolds et al. 2016). These observations indicate that in 2021, more than a decade following the end of the Millennium Drought, the Ruppia Community continues to exhibit a recovery trajectory. Only in the most recent sampling periods (Paton et al. 2021, Lewis et al. 2022) have we observed numerous sites reaching seed bank densities > 2,000 seed m^{-2} (Figure 6) currently set as the target for a resilient Ruppia Community (Department for Environment and Water 2020b). The most recent season (2021 Reproductive) also exhibited high numbers of turions forming (Paton et al. 2021, Lewis et al. 2022) (Figure 6).

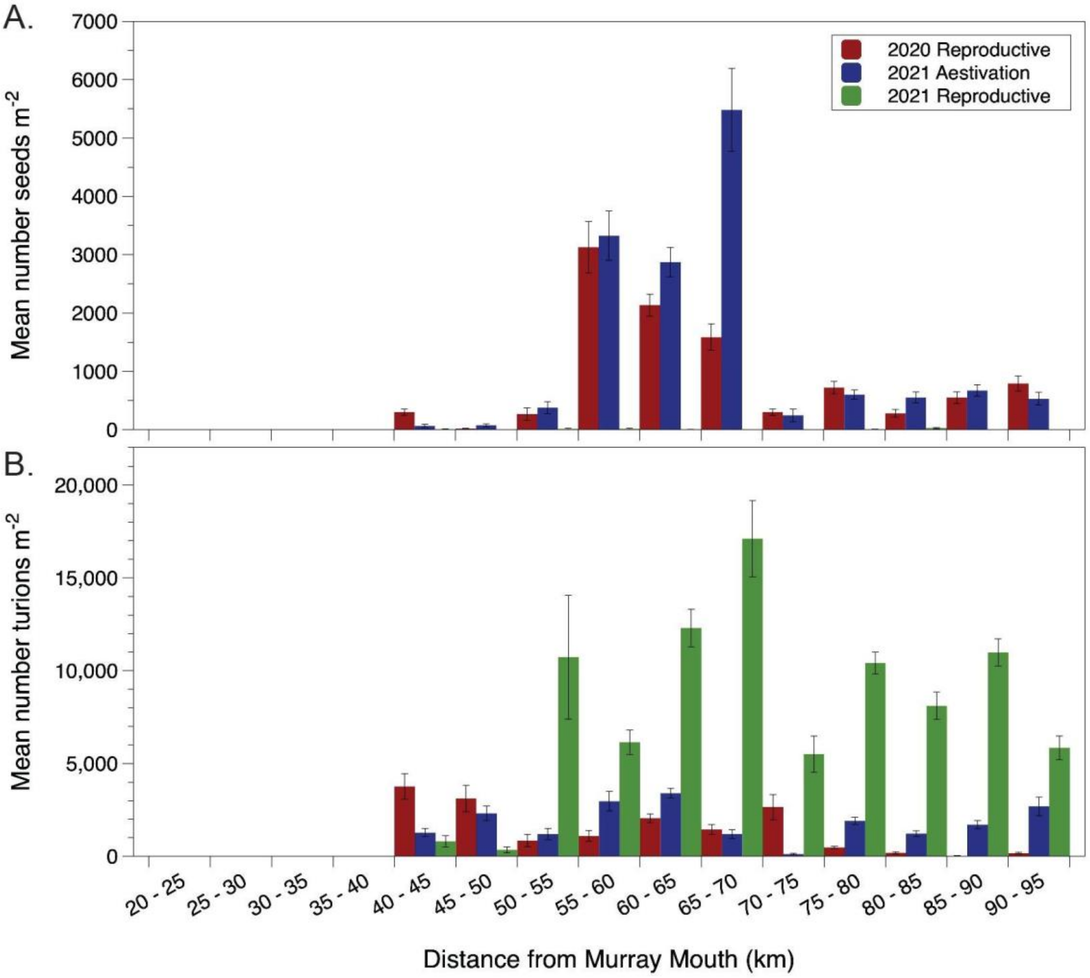

Figure 6. Reproductive effort measured during seasonal surveys (Lewis et al. 2022) A. seed bank (number of seeds per 7.5 cm diam. 8 cm deep core scaled to m^{-2}) of *Ruppia* sp. and B. turions being formed (number of turions per 7.5 cm diam. 8 cm deep core scaled to m^{-2}). For reference some locations and distance from Murray Mouth: Noonameena – 40 km, Parnka Point – 60 km, Woods Well – 77 km, Salt Creek – 93 km. Note, surveys did not occur <40 km from Murray Mouth.

There is a diverse range of literature on aspects of the aquatic macrophyte community in the Coorong. We draw on the resources in these publications that include monitoring reports, research project reports, journal publications, books and reviews to inform this Restoration Strategy and they are cited herein. Key resources include:

- Reviews of the Ruppia Community in the Coorong (Nicol 2005, Paton et al. 2011, Collier et al. 2017, Nicol et al. 2018, Asanopoulos and Waycott 2020).
- The Ruppia Community in the context of the Ramsar listed Coorong and Lakes Alexandrina and Albert wetland (Phillips and Muller 2006, Paton et al. 2015b, Brookes et al. 2018, Department for Environment and Water 2020b, 2021c, b).
- Restoration of the Ruppia Community following the Millennium Drought (2001–2010) (Department of Environment and Heritage 2010, Paton and Bailey 2010, Paton et al. 2011, McCarron 2013, Department of Environment Water and Natural Resources 2014b, Paton et al. 2016a, Paton et al. 2018a).
- Ongoing monitoring of the Ruppia Community for The Living Murray initiative (Paton and Bailey 2012, Paton and Bailey 2014, Paton et al. 2015a, Paton et al. 2016b, 2017a, Paton et al. 2019, Paton et al. 2020, 2021).
- The natural history of the Coorong and adjacent region including significant information on the Ruppia Community (Noye 1973, Womersley 1975, Paton 2010, Mosley et al. 2018).

The following documents inform and guide the management, monitoring and reporting for the Ramsar site as a whole:

- An Ecological Character Description (ECD), (Phillips and Muller 2006, Department for Environment and Water 2021b).
- The Ramsar Information Sheet (RIS) (Department of Environment 2013).
- A Ramsar Site Management Plan (RMP) (Department of Environment and Heritage 2000, Department for Environment and Water 2021a).

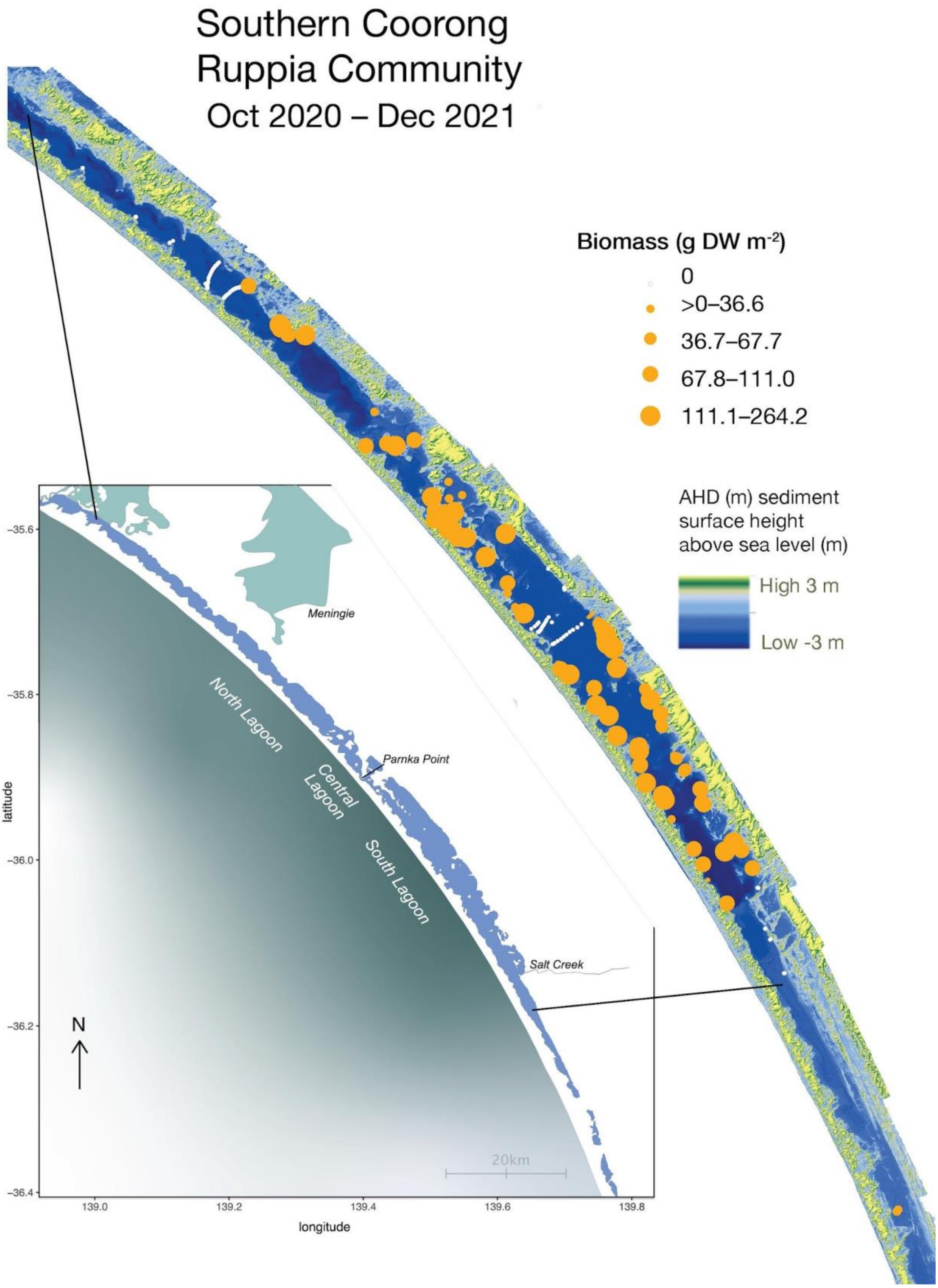

Figure 7. Ruppia Community biomass (g dry weight (DW) m^{-2} for cores) across the central and southern Coorong; surveyed in December 2021 (Lewis et al. 2022), points overlayed on the sediment height above sea level (AHD, m) (Hobbs et al. 2019), data only shown for survey locations, including those that had an absence of a Ruppia Community; white dots. Refer to Figure 2 for additional details on locations.

1.4 Aquatic macrophyte recovery following loss in coastal lagoons and estuaries

Seagrasses and other submerged aquatic vegetation are typically dominant macrophytes in estuaries and coastal lagoons (e.g. Pérez-Ruzafa et al. 2011, Christia et al. 2018). There is a long history of anthropogenic disturbance impacting seagrass communities worldwide (Wyllie-Echeverria and Wyllie de Echeverria 2013). Recognised cultural values associated with seagrasses include their importance as hubs for recreation and tourism and their fundamental role in providing havens for iconic and culturally important biodiversity, including dugong and manatee, breeding grounds for species of fish and invertebrates and productive foraging areas for birds (Wyllie-Echeverria et al. 1999, Iyengar 2018, McKenzie et al. 2021, Unsworth and Butterworth 2021). A range of ecosystem services are attributed to southern Australian temperate seagrasses, including the provision of food (fisheries), regulation of our climate (sequestration of carbon), treating our waste (nutrient cycling) and protecting our shorelines from storm damage (sediment stabilisation) (Gaylard et al. 2020). However, one of the most highly valued ecosystem services that aquatic macrophytes provide is their ability to uptake and process nutrients, which improves water quality and reduces the likelihood of eutrophication (Moore 2004, Orth et al. 2020). These positive ecological functions in aquatic ecosystems, particularly their ability to improve habitat quality for other species, make seagrasses an important component for consideration in any aquatic ecological restoration program (Comin et al. 1990, Takamura et al. 2003, Krumholz 2019).

Unfortunately, aquatic ecosystems, including wetlands, are among the most endangered in the world, primarily due to anthropogenic activities (Hails and Peck 2007, Camacho et al. 2012). It is well documented that seagrasses are declining worldwide at diverse spatial and temporal scales (Orth et al. 2006c, Waycott et al. 2009, O'Brien et al. 2018, Turschwell et al. 2021, Buelow et al. 2022). Declining water quality including eutrophication resulting from anthropogenic disturbances is one of the most common causes of deterioration of estuaries and coastal lagoons worldwide (Perrow and Davy 2002, Mitsch and Gosselink 2015, Waltham et al. 2020). There is a well-established link between the presence of aquatic macrophyte communities, such as seagrasses, and the ecological health of coastal ecosystems (e.g. Short and Wyllie-Echeverria 1996, Orth et al. 2006b, Scanes et al. 2020). Ecosystem health assessments often utilise the loss of seagrasses as an indicator of ecological state due to the association of seagrass abundance and community composition with anthropogenic pressures, such as poor water quality and water availability (Steward et al. 2005, Duffy et al. 2019, Scanes et al. 2020). Despite recent large-scale seagrass habitat recovery success stories providing evidence of the potential for recovery if conditions are suitable (McGlathery et al. 2012, Orth et al. 2020, Tan et al. 2020) there is an ongoing global decline of seagrasses and other coastal ecological communities (Turschwell et al. 2021, Buelow et al. 2022).

Different ecological restoration strategies have been adopted to facilitate the recovery of seagrasses and other aquatic macrophytes in estuaries, coastal lagoons and bays in which there have been significant losses (Paling et al. 2009, Elliott et al. 2016, Katwijk et al. 2016, Tan et al. 2020, Sinclair et al. 2021). A critical element of any ecological restoration action is to remove or limit the cause of the decline or the impacts will be ongoing (De Wit et al. 2017, SERA 2021b). In estuaries and coastal lagoons, management actions to restore ecological function or specific habitat, including seagrass habitat vary in approach and scale particularly where there are different costs or levels of significance to the potential restoration actions (Oreska et al. 2021). Seagrass recovery can be encouraged via ‘passive’ or secondary approaches such as improving water quality entering a catchment (Waycott et al. 2005) or improving connectivity with rivers or ocean through mechanical means such as dredging. Alternatively, ‘active’ restoration efforts involving distribution of seeds or vegetative structures to re-establish aquatic macrophyte communities can be implemented.

Here we summarise a series of examples that have adopted different approaches to recover aquatic macrophyte communities in coastal lagoons and estuaries. We briefly summarise the restoration strategy adopted (Table 1), and where known, the current status of each system. These examples, described in more detail in the following section, provide some context for understanding steps in decision making associated with a Ruppia Community Restoration Strategy for the Coorong.

Table 1. Summarised examples of locations where restoration strategies or interventions have been adopted to restore seagrass or marine macrophyte communities based on published literature.

Location	Cause of decline	Scale of impacted area	Intervention activity restoration cycle	Restoration action	Restoration response	Key citations
St Lucia Estuary, South Africa	Intensification of land use Drought Decline in water quality Increasing salinity Eutrophication	Variable with climatic and environmental conditions, i.e. salinity and water depth	Improved water quality through connectivity Habitat restoration through non-intervention (passive)	Efforts to manage water quality (i.e. increase water levels, decrease salinity), including increase inflows from mouth and connected rivers via channel construction and mouth dredging	Response in macrophyte distribution not quantified	Taylor et al. (2006) Russell et al. (2009) Riddin and Adams (2012) Rautenbach (2015) Cyrus et al. (2020) Forbes et al. (2020)
Peel-Harvey Estuary, Western Australia	Decline in water quality due to intensification of land use Eutrophication Algal blooms	>130 km^2 of estuary eutrophic	Reduce eutrophication to limit algal blooms Decrease residence times through increasing water exchange (ocean-connection)	Passive habitat restoration Efforts to increase water inflows via channel construction led to improved habitat quality	Macrophyte monitoring program abandoned in 2000. To date, no catchment or estuary water quality monitoring program in place Indication that initial response was insufficient to support seagrass recovery EPA surveys in 2017-18 indicated increased macrophyte biomass in southern shallows	Wilson et al. (1999) Elliott et al. (2016) Krumholz (2019)
Wilson Inlet, Western Australia	Decline in water quality with closure of ocean connection increasing residence times and flows Eutrophication	Not quantified but described as significant fluctuations (increases and decreases) in *Ruppia megacarpa* distribution and biomass Nutrients/ eutrophication led to increase in *Ruppia* becoming problematic for human uses and changing ecosystem function	Re-establish ocean connection reducing residence times, and nutrient accumulation	Passive habitat restoration Intervention to establish ocean connection (dredging)	Reduction in nutrients held in system Stabilised *Ruppia megacarpa* biomass to levels prior to closure of ocean connection	Lukatelich et al. (1987) Carruthers and Walker (1999)
Venice Lagoon, northern Italy	Decline in water quality due to increasing	Almost completely disappeared from northernmost region	Eutrophication reduction through reduced clam fishing resulted in suitable conditions to attempt	Vegetative (rhizome) transplantation approx. 75,000 transplants	1,000-1,500 ha of restored seagrass meadow	Sfriso et al. (2017) Sfriso et al. (2021)

Location	Cause of decline	Scale of impacted area	Intervention activity restoration cycle	Restoration action	Restoration response	Key citations
	anthropogenic activity Eutrophication Clam fishing with mechanical dredges		restoration intervention via direct planting	(*Zostera noltei, Z. marina* and *Ruppia cirrhosa*)		
Whangarei Harbour, northern New Zealand	Decline in water quality Decline in water clarity through dumping dredge spoils	Estimated 1,000 – 1,500 ha of seagrass meadows	Improved water quality due to improved management of dredging and runoff impacts Habitat restoration intervention initiated via direct planting	Transplantation of cores containing shoots and rhizome (*Zostera muelleri* syn. *Zostera novazelandica*) into ~18 m^{-2} made up of numerous smaller (up to 0.5 m^{-2}) sods across transplant sites over 6,000 m^{-2}	Estimated to have re-established to 40% (2,400 m^{-2}) of transplant site within 2 years Donor site recovered within 9 months	Reed et al. (2004) Matheson et al. (2017)
Virginia coastal bays, USA	Decline in water quality Seagrass decline in 1930s due to wasting disease associated with eutrophication Severe weather events (hurricane)	Greater than the current area recovered, >3,600 ha	Water quality improved but recruitment limited by isolation from seed sources Direct broadcast seeding onto sediments	Large-scale seagrass direct seeding (*Zostera marina*) 70 million *Z. marina* seeds spread over 21 years	3,612 ha of restored seagrass meadows through restoration	Orth and Moore (1983) Orth et al. (2006a) Reynolds et al. (2013) Reynolds et al. (2016)

1.4.1 Examples of restoration actions to recover aquatic macrophyte communities in estuaries and coastal lagoons

The marine macrophyte communities of the St Lucia Estuary, South Africa, were affected by anthropogenic activity and drought occurred between 2001 and 2004, which led to low water levels, increased salinity (>100 g L^{-1}) and closure of the river mouth preventing marine inflows (Taylor et al. 2006). Typically, St Lucia Estuary has highly variable marine (dependent on river mouth connectivity) and freshwater inflows, which are largely controlled by management decisions, which in-turn alter environmental variables (salinity, water depth, turbidity) (Riddin and Adams 2012, Rautenbach 2015). These conditions were still persisting in 2010, with macrophyte distribution and abundance continuing to decline, when a comprehensive restoration program was mandated (Cyrus et al. 2020, Forbes et al. 2020). Several strategies to increase inflows were initiated aiming to restore the aquatic macrophyte community. Strategies adopted to increase inflows included allowing extra river water to flow into the affected areas via channels and dredging of the river mouth. These strategies were successful in lowering salinity and increasing water levels, however the benefits to the aquatic macrophyte community were variable (Cyrus et al. 2020) (Table 1). The submerged aquatic macrophyte community in the St Lucia Estuary was found to be resilient and persisted as long as water levels were maintained. Recovery from periods of stress associated with water level recession and desiccation was quick once adequate water levels returned due to prolific flowering that supported subsequent recolonisation (Taylor et al. 2006).

The Peel-Harvey Estuary, Western Australia, was subject to natural and anthropogenic disturbances, including; eutrophication causing algal blooms and system degradation (summarised in Krumholz 2019). The issues associated with eutrophication became apparent in the 1960s and 1970s where large-scale losses of aquatic macrophytes (seagrasses) were observed and blooms of blue-green algae became regular occurrences (Krumholz 2019). Strategies to increase inflows and reduce eutrophication were implemented in the early 1990s with a new channel cut to improve flows. One-year after construction, significant reductions in nutrient loads and macroalgae blooms and an increase in macrophyte biomass were observed (Krumholz 2019). While some issues with blue-green algae and filamentous algae continued, the management strategies were successful in improving overall water quality and reducing eutrophication and increases in macrophyte populations were observed (Elliott et al. 2016, Krumholz 2019). Initial indications suggested that management strategies were inadequate to support long-term seagrass recovery (Wilson et al. 1999), however surveys in 2017-18 observed increased seagrass biomass in the shallows of the southern Harvey estuary (Krumholz 2019).

Wilson Inlet, Western Australia, a seasonally closed river mouth experienced cumulative high nutrient content and resulting eutrophication, largely as a result of reduced inflows (Dudley et al. 2001). However, as the system was previously highly oligotrophic (very low levels of nutrients), anthropogenic nutrient inputs increased the biomass of *Ruppia megacarpa.* Ongoing nutrient loading contributed to some algal blooms and an unstable, fluctuating, significant volume of seagrass biomass, which was viewed by some of the community as problematic (Western Australian Department of Environment 2003). To manage nutrient concentrations within the system, an opening between the river mouth and ocean is required. To facilitate an opening between the river and ocean, dredging has occurred at the end of winter for the last ~60 years (Reichwaldt and Thomson 2018).

The Venice Lagoon in northern Italy was historically dominated by aquatic macrophytes, predominantly meadow-forming seagrasses (Sfriso et al. 2017). Over four-years, 75,000 transplants of vegetative material (rhizomes) from four seagrass species were undertaken, forming ~10-15 km^2 of meadows (Sfriso et al. 2021). Despite the success of this restoration strategy, it was observed that transplants failed to survive in locations affected by freshwater outflows rich in nutrients and particulate matter (Sfriso et al. 2021). This case again highlights the importance of environmental factors such as water quality in the success of restoration activities and the need to monitor environmental parameters in waterbodies and sediments to identify the best conditions for restoration (Sfriso et al. 2021).

Whangarei Harbour in northern New Zealand had extensive seagrass beds prior to the 1970s which occupied ~1,000-1,400 ha (Reed et al. 2004, Matheson et al. 2017). Anthropogenic activity, including urban and industrial discharges, reduced water clarity and caused plants to become smothered by dredge spoil. These environmental conditions contributed to a significant decline in seagrass extent over two decades, leaving only small remnant beds. In 2008, a trial began to transplant seagrasses from the largest remnant patch to an area where loss had been observed. After two years, transplanted seagrass had survived and flourished in one of three transplant methods trialled, 'sod and sprig' (Matheson et al. 2017). Another trial was conducted in 2012 using several other sites, where 24 seagrass transplants spread to occupy ~750 square metres within four years (Matheson et al. 2017). An overall estimate suggests that seagrass meadows now occupy ~40% of their former range, taking into account restoration efforts and natural recruitment (Matheson et al. 2017).

The Virginia Coastal Bays, USA, are one of the most successful large-scale seagrass restoration efforts globally (Orth et al. 2010, Orth et al. 2020). The restoration strategy in this large scale coastal lagoon system, which began in 2001, used direct broadcasting (manual spreading of seed) of eelgrass seed to restore large areas of macrophyte habitat (Orth et al. 2010, Reynolds et al. 2016, Orth et al. 2020). More than 74.5 million seeds were broadcast into 536 plots over 213 ha, which resulted in 3612 ha of seagrass meadow, where it was previously scarce or absent (Orth et al. 2020). This success highlighted that favourable environmental conditions, such as low turbidity and nutrient load, and ongoing management to maintain these conditions, are critical for restoration efforts (Orth et al. 2006c, Orth et al. 2010, Reynolds et al. 2013, Reynolds et al. 2016, Orth et al. 2020).

Recent reviews of seagrass restoration provide a range of examples where the causes of habitat decline need to be removed and the physical/chemical conditions of the ecosystem repaired, in order to assist with potential habitat recovery (Paling et al. 2009, Elliott et al. 2016, Katwijk et al. 2016, Orth et al. 2020, Tan et al. 2020, Waltham et al. 2020, Sinclair et al. 2021, Buelow et al. 2022).

It is worth noting, that the hydrological, physical and chemical environment of the southern Coorong experiences a range of conditions without analogy. Consideration of similar systems is difficult when the Coorong experiences salinity across a range from less than 0.5 x marine (35 g L^{-1}) to more than 3 x marine in moderate years (Figure 3A). Annual evaporation in the South Lagoon is a significant factor in the seasonal salinity cycle where if limited lower salinity water enters the system in the cooler, wetter months a rapid return to high salinities will be experienced in warmer, drier months (Mosley et al. 2018). These factors are coupled with limited additional water availability also controlled through barrage releases and south-east flows through Salt Creek, and constricted connectivity in the central section (e.g. Figure 8). These environmental factors make applying the global learnings from seagrass restoration complex and challenging in the context of the Coorong.

Figure 8. View of the central section of the Coorong, opposite Rabbit Island (-35.854223° 139.384918°) looking south in January 2021 when water levels were low. Note the darker areas in the water are algal covered remnants of the annual Ruppia Community, water column salinity was > 100 g L^{-1}. Photograph provided by Geoff Gallasch, used with permission. Refer to Figure 2 for additional details on locations.

2 Case study: Post Millennium Drought translocation of *Ruppia tuberosa* in the Coorong

2.1 Introduction

Following the Millennium Drought influences on the Coorong (2001–2010), improvements were observed in environmental variables (water level and salinity), however an increase in the distribution and abundance of the Ruppia Community was slow to occur (Collier et al. 2017, Nicol et al. 2018, Paton et al. 2019). The annual growth cycle of *Ruppia tuberosa* relies on its ability to flower during the spring to early summer growing period and produce seed prior to receding water levels and salinity increasing to suboptimal levels (>100g L^{-1}) (Asanopoulos and Waycott 2020) (Figure 5). Seeds then remain in the sediment and the above ground plant parts die off. Alternative life cycle pathways also occur (vegetative persistence of whole plants or the formation of turions) (Brock 1982). The reliance on seed banks is fundamental to survival in highly perturbated environments (e.g. Kilminster et al. 2015) such as the extreme conditions of the Coorong South Lagoon (Collier et al. 2017, Nicol et al. 2018). Following extended periods that are favourable to germination but unfavourable to the generation of a seed bank, the loss of the seed bank may occur, reducing the ability of meadows to re-establish once favourable conditions return (Paton et al. 2011, Frahn et al. 2012, Frahn and Gehrig 2015, Paton et al. 2015b). The slow rate of recovery has been attributed to the loss of the seed bank of *Ruppia tuberosa* (Frahn et al. 2012, Frahn and Gehrig 2015), and likely other members of the Ruppia Community. This loss occurred over the extended drought period, where a majority of the surviving Ruppia Community was unable to complete its lifecycle due to very low water levels and high salinity (Department of Environment Water and Natural Resources 2014a).

Recognising the decline in the Ruppia Community post-Millennium Drought, seed bearing sediments from nearby salt lakes were translocated to strategic locations in the Coorong South Lagoon (Department of Environment Water and Natural Resources 2014a, Sinclair et al. 2021). The seed bank donor site, Lake Cantara, is an ephemeral lake, located ca. 15 km southeast of the Coorong (Figure 9). Following the translocation works, there was very limited evaluation of the success of the restoration effort. In this study, we sought to determine whether sites that received translocated seed-bearing sediment were performing better than nearby sites with comparable environmental and geographical characteristics.

The technical feasibility assessment for restoration (Department of Environment and Heritage 2010) and subsequent research on the biology of the Ruppia Community to inform proposed intervention actions (Paton et al. 2011) led to the implementation of on-ground restoration efforts between 2012 and 2014 (McCarron 2013, Ryan 2015, Paton et al. 2016a). Ruppia Community seed bearing sediments were distributed at two locations in 2012-13 (Figure 9; Woods Well (WW) and Policeman Point (PP), the seeds sourced from Lake Cantara). Translocated sediments covered the surface layer (up to 0.15 m) of sediment at each receptor site (Figure 10; Lake Cantara (LC)). Evaluation of the recovery of the Ruppia Community following seed distribution in this first season was conducted by honours student Victoria McCarron (University of Adelaide Honours Thesis; McCarron 2013). The following year (2013-14) an additional three locations (Figure 10; Fat Cattle Point (FCP), Jack Point (JP) and Seagull Island (SI)) received translocated seed bearing sediment, again from Lake Cantara (Ryan 2015, Paton et al. 2018a). A short published account of translocation outcomes for all five locations was presented at a national workshop (Paton et al. 2018a) in addition to the honours thesis (McCarron 2013) and a summary of available data was included in the Ecological Character Description for *Ruppia tuberosa* in the Coorong (Paton et al. 2015b). Ongoing monitoring or collection of data for the purpose of evaluating the trajectory of recovery at these sites or areas nearby was not routinely undertaken after these initial surveys.

During the development of this Restoration Strategy for the Ruppia Community in the Coorong, we identified the minimal evaluation of previous restoration actions as a significant knowledge gap. We undertook targeted surveys in 2020-2021 to identify if '*The translocation works conducted from 2012-2014 led to significant improvement in the condition and resilience of the Ruppia Community when compared with similar locations where no direct translocation activities have occurred*'.

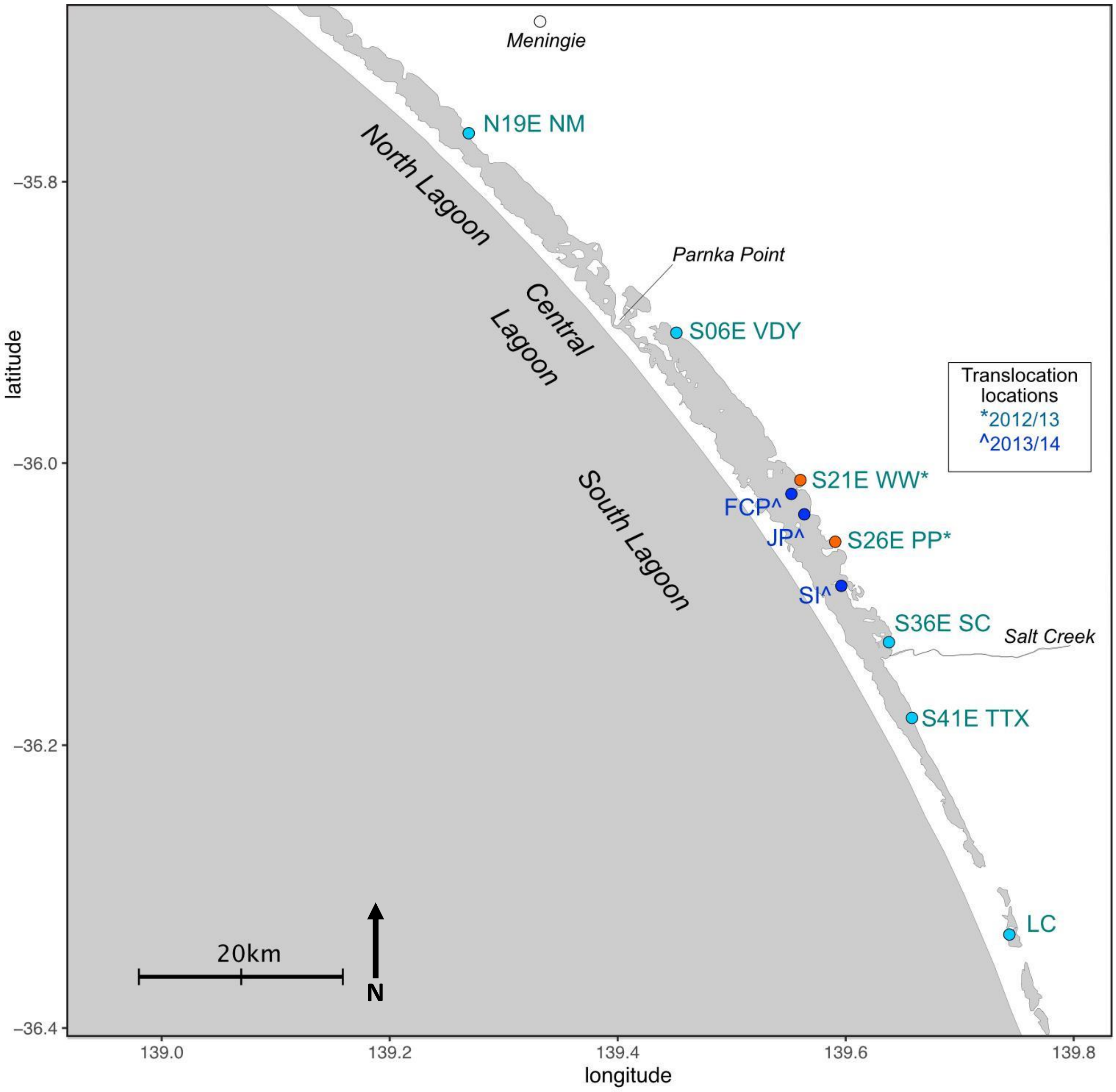

Figure 9. Locations of Coorong sites and regions, codes refer to long-term monitoring sites for The Living Murray (TLM) condition monitoring program (Paton et al. 2020). The locations where restoration sites were established are also indicated (2012-13 translocation locations orange circles: WW = Woods Well and PP = Pelican Point; 2013-14 dark blue circles: FCP = Fat Cattle Point, JP = Jack Point and SI = Seagull Island). Seed donor site LC = Lake Cantara).

2.1 Seed based *Ruppia tuberosa* restoration in the Coorong (2012-2014)

After nearly a decade of the Millennium Drought (2001–2010) impacting the Coorong, intervention works were undertaken to assist in the recovery of *Ruppia tuberosa*; a keystone resource in the ecosystem that is fundamental to many ecological processes. The following assumption was documented in the technical feasibility assessment undertaken by the Department of Environment and Heritage in 2010:

> *'Even if water level and salinity in the Coorong are successfully returned to target levels for ecosystem health, some intervention may be required to encourage the timely re-establishment of Ruppia in areas from which it has been lost.' (Department of Environment and Heritage 2010)*

To improve the likelihood of *R. tuberosa* (which we now recognise as the Ruppia Community) recovery in the Coorong South Lagoon a large-scale transfer of seed-bearing sediment was proposed. The operation was conducted over the warmer months of 2012-2014, in partnership with the Traditional Owners; the

Ngarrindjeri community (Department of Environment Water and Natural Resources 2014b). This method was feasible as *R. tuberosa* seeds are ~1 mm in size, black and tear-drop shaped, are highly resistant to environmental extremes and form a resilient seed bank in the surface sediments (Department of Environment and Heritage 2010). *Ruppia tuberosa* seed is tolerant of complete drying in extreme hypersaline sediments (salinity >150 g L^{-1}) and exposure to high temperatures during summer months. *Ruppia* seeds, as well as seeds of *Althenia* which is often found growing with *Ruppia* in hypersaline lakes and lagoons of South Australia, can be found in many seasonally exposed lake bed sediments in the South East region (Brock 1982). A working group with technical expertise in the region, seagrass and aquatic plant biology, hydrology of the Coorong and direct involvement in establishing the restoration options was convened to support and provide advice on the proposed actions.

2.1.1 Methods

Lake Cantara, an ephemeral lake immediately south of the Coorong, was identified as a site where seed densities were very high in surface layers of sediment at the end of the Millennium Drought (Paton et al. 2011, Collier et al. 2017), and was therefore selected as the donor site. The technical working group agreed to constrain the area to be impacted at the donor site to <5% area annually and placed a minimum threshold on available seed banks of >2,000 seeds m^{-2}.

Seed excavation at Lake Cantara involved scraping a 0.10–0.15 m surface layer containing the *Ruppia* seed bank. This sediment was removed mechanically using a small excavator along the edge of the salt pan during late summer and early autumn when the lake was dry (Figure 10) (Ryan 2015). Track mats were used to reduce the impact of the excavator on the surface of the donor site by distributing the load of the tractor and reducing direct tyre or tread damage (Ryan 2015). A total of 712 tonnes of sediment containing seeds was bagged and translocated to the five restoration locations in the Coorong South Lagoon (Table 2, Figure 10). The sites were chosen based on water level predictions, following advice on water depths preferences for *R. tuberosa* between 0.3–1.0 m (Nicol 2005). More than 40,000 bags of sediment were translocated during the two years of the project (Ryan 2015, Paton et al. 2018a). A total area of approximately 60 ha across the five sites (Figure 9) was seeded in two sequential two seasons, 2012-13 and 2013-14 (Table 2).

Table 2. Summary of *Ruppia* translocation activities in the Coorong South Lagoon during the period 2012-2014 (Table adapted from Paton et al. 2018).

SITE, NAME AND COORDINATE (DECIMAL DEGREES)	YEAR OF TRANSLOCATION	AREA (HA)	TONNES SEDIMENT	EST. NO. SEEDS ($X10^6$)	EST. NO. SEEDS M^{-2}
Policeman Point	2012/13	10	142	73.8	738
Woods Well	2012/13	10	140	72.9	729
Fat Cattle Point*	2013/14	11.5	121	83.9	729
Jack Point	2013/14	18	192	133.4	741
Seagull Island	2013/14	9.5	117	81.3	856
TOTAL		**59**	**712**	**445.3**	-

*There were monitoring sites in north (FCPN) and south (FCPS) of the area that had seed laden sediments translocated.

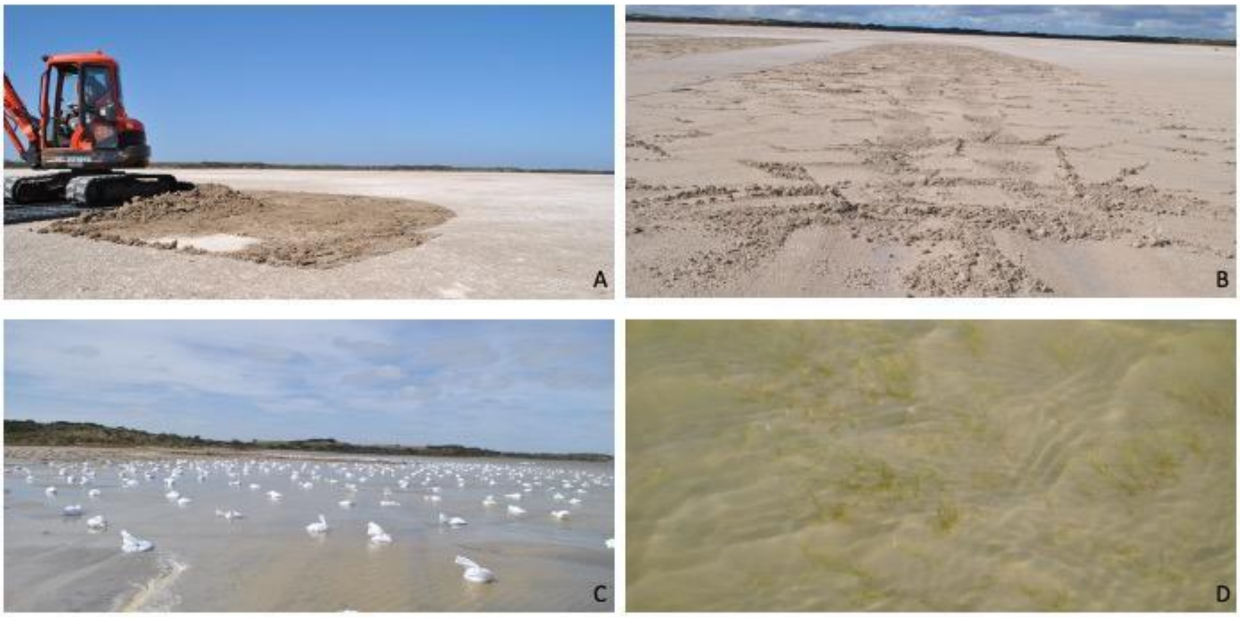

Figure 10. Lake Cantara (seed donor site) used for restoration of *R. tuberosa* in the Coorong through seed laden sediment translocation. A. large scale scraping of the upper surface of dried sediment to 0.10-0.15 m depth containing the sediment seed bank using tractor running on track mats; B. post-scraping at location where large scale seed harvesting occurred; C. bags of scraped sediment containing *R. tuberosa* seeds were relocated to storage sites in the Coorong and kept dry until water levels began to rise in autumn then emptied onto the exposed sediment surface of the Coorong just prior to full seasonal inundation; D. post translocation Ruppia Community growing in the shallow at a translocation site during winter (Photos by Kat Ryan, Department of Environment, Water and Natural Resources (DEWNR)).

2.1.2 Results

Ruppia established across each of the translocation sites within three months of the sediment transfer, as water levels rose during autumn (McCarron 2013, Department of Environment Water and Natural Resources 2014b, Ryan 2015, Paton et al. 2016a). All restoration sites showed an emergence of *Ruppia* seedlings with abundant patches established in following years (Figure 11). At the two sites with an extra season of data, Woods Well and Policeman Point (Figure 11), the proportion of cores with shoots present increased with each sampling time, noting there were no samples for shoot counts when water levels were low in February 2015, the peak of the summer period.

The recovery of these areas followed a positive but erratic trajectory observed with the two years of monitoring data collected (Figure 11). Observations of nearby sites that were not in the direct seeded zones and included in long-term monitoring efforts exhibited a general positive trend over this period (Paton et al. 2018a). For example, at one long-term monitoring site, Policeman Point, there were zero shoots in sampling cores in annual monitoring of the site prior to translocation in 2011 and by 2015, 37.5% of cores had shoots (Paton et al. 2018a). Water levels experienced over the monitored period (2011-2015) were adequate for successful reproduction (Figure 12).

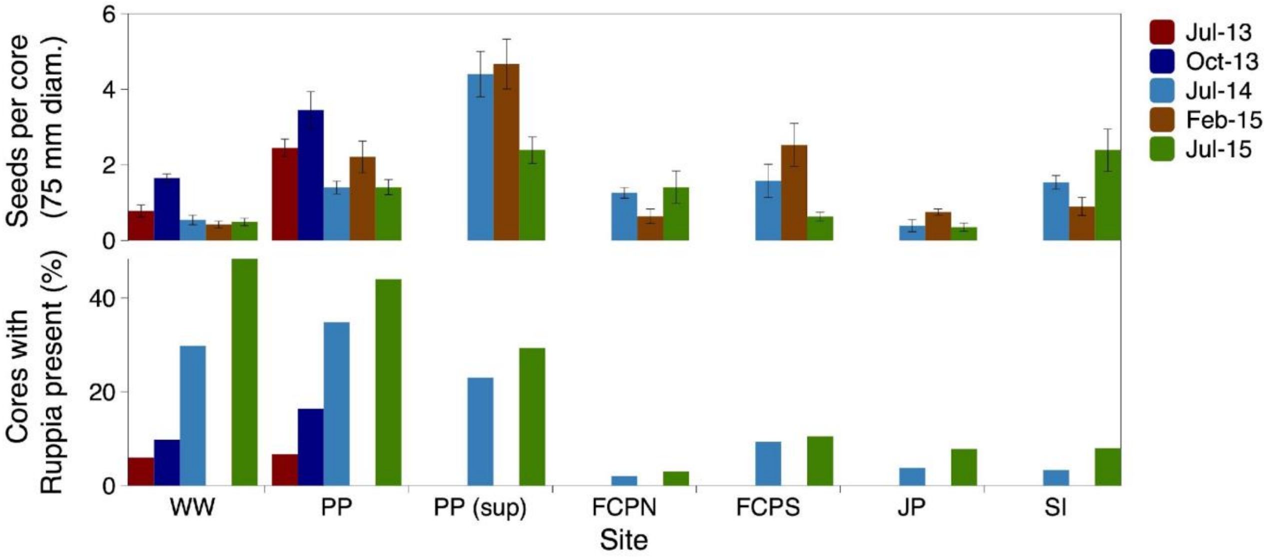

Figure 11. Reported outcomes of post seed translocation monitoring (Paton et al. 2015b). Sites WW and PP received translocated sediments in 2012-13, the remainder in 2013-14 (Department of Environment Water and Natural Resources 2014a, Ryan 2015). Data source notes: Mean ± s.e. *R. tuberosa seeds* per core (75 mm diameter and 40 mm deep) at sites following translocation of surface sediment containing seeds from Lake Cantara in Autumn 2013 (WW, PP) in both Autumn 2013 and 2014 (PPsup; which received second translocation) and in Autumn 2014 (FCPN, FCPS, JP, SI). Missing data points are due to no sampling in that period as described in Paton et al. (2015b). Percent of cores (75 mm diameter and 40 mm deep) with *R. tuberosa* shoots present following translocation of surface sediment containing seeds from Lake Cantara in Autumn 2013 (WW, PP) in both Autumn 2013 and 2014 (PPsup) and in Autumn 2014 (FCPN, FCPS, JP, SGI).

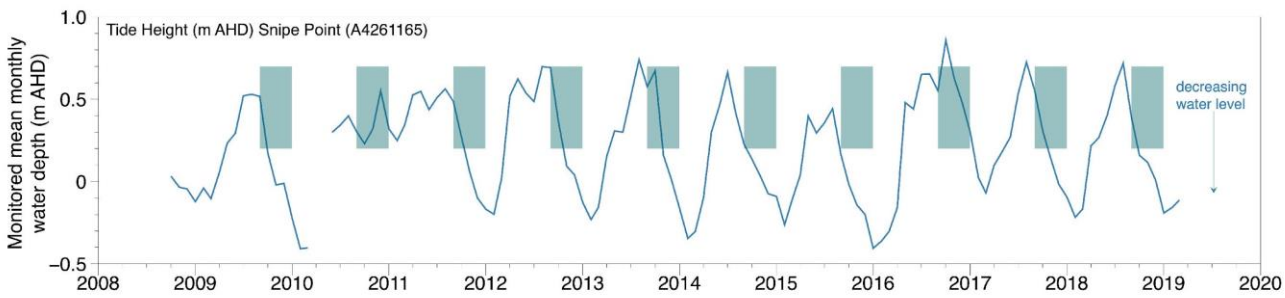

Figure 12. Mean monthly water depth (tide height, m) at the Snipe Island (station A4261165) monitoring station calibrated to represent depths as m AHD (Australian Height Datum) maintained by the Department for Environment and Water (DEW) derived from Water Data SA (https://water.data.sa.gov.au/). The shaded bands represent the one standard deviation range of water depths where the Ruppia Community grows during its reproductive season (September–December) (Figure 4A).

2.1.3 Discussion

The *R. tuberosa* translocation efforts in the Coorong South Lagoon between 2012-2014 were successful based on observations made during the first two seasons following site works (McCarron 2013, Paton et al. 2018a), with good germination and modest recruitment observed at the sites of translocation. As no subsequent monitoring was undertaken the long-term performance of the restoration actions is a knowledge gap.

The long-term persistence of the Ruppia Community requires maintenance of adequate water levels during spring, when *Ruppia* flowers and sets seed (Phillips and Muller 2006, Paton et al. 2015b, Collier et al. 2017, Brookes et al. 2018, Asanopoulos and Waycott 2020). Adequate water levels are one of the critical elements for planning Ruppia Community restoration. Since restoration works in 2014, mean monthly water levels during spring and summer have been relatively poor for reproduction, with the exception of 2016. In 2016, water levels were comparable to those supporting plant reproduction from 2020-2022 (Figure 12).

Other factors will limit the recovery of Coorong *Ruppia* habitat, including interactions with external factors such as filamentous algal blooms, inadequate light due to poor water quality and inhibition to seed germination from sediment chemical constituents (Mosley and Hipsey 2019, Hipsey et al. 2020, Mosley et al. 2020, Waycott 2020, Waycott et al. 2020a). In particular, poor water quality and overall total nutrient loads in the Coorong ecosystem are leading to conditions that inhibit the return of dense *Ruppia* meadows in the southern Coorong (Collier et al. 2017, Mosley et al. 2020, Paton et al. 2020, Waycott et al. 2020a).

2.2 Evaluation of seed based *Ruppia tuberosa* translocation sites (2021-2022)

The ongoing success of *R. tuberosa* restoration actions from 2012-14 is a knowledge gap due to the absence of ongoing monitoring. The evaluation of relative performance for restoration actions taken some time ago, in this case 6-8 years, required a baseline reference for comparison purposes. The Condition Monitoring Plan for The Living Murray – Lower Lakes, Coorong and Murray Mouth Icon Site, *R. tuberosa* (Paton et al. 2017b) has well established targets for the aquatic macrophyte community to meet. These do not provide local reference for how the sites were recovering without the direct action of seed laden sediments having been translocated to the site. This field study aimed to determine if areas where the translocation works conducted in 2012-2014 were detectably better performing than areas without restoration actions, under similar location conditions and areas of the Coorong.

2.2.1 Methods

Field surveys and sampling 2021-2022

We conducted a series of surveys in 2021-2022 to assess Ruppia Community condition and resilience.

The sites surveyed as part of this study (Table 3) included four sites, which were located within the areas where translocation works occurred in 2012-2014 (Figure 13). We also selected a set of four non-translocated, control sites paired to the translocated sites. These paired sites were situated as close as possible to the translocation sites and had similar geographic and environmental traits (elevation, exposure, sediment type) (Figure 13). We also undertook surveys at the seed bank donor site in Lake Cantara and a non-donor, control site to quantify the effects of seed bank removal on the local Ruppia Community within Lake Cantara (Figure 14).

We used the metric of plant biomass (g DW m^{-2}) to assess condition and two measures to quantify resilience; seed bank (number of seeds m^{-2}) and turion density (number of turions m^{-2}) (Lewis et al. 2022). The condition surveys to assess biomass were conducted on the 15-16 June 2021 at translocation and non-translocated (control) sites and 12 October 2021 at the Lake Cantara seed bank donor site and non-donor site (control). Resilience surveys to measure seed and turion abundance were undertaken following receding water levels on the 16 and 24 March 2022.

Table 3. Locations of survey sites for surveys of current condition of the Ruppia Community. Translocated sites were determined based on documentation of the translocation activities by the Department for Environment and Water (Ryan (2015), non-translocated sites were in the same broader geographic area with comparable elevation, exposure, sediment type.

SITE	TYPE	LATITUDE	LONGITUDE	CONDITION SURVEY DATES	RESILIENCE SURVEY DATES
Woods Well	translocated	-35.993789°	139.537574°	15-16 June 2021	16 or 24 March 2022
	non-translocated	-36.000244°	139.537967°	"	"
Fat Cattle Point	translocated	-36.016289°	139.559530°	"	"
	non-translocated	-36.024339°	139.568040°	"	"
Jack Point	translocated	-36.037651°	139.572820°	"	"
	non-translocated	-36.048937°	139.577603°	"	"
Policeman Point	translocated	-36.058914°	139.586484°	"	"
	non-translocated	-36.070885°	139.597806°	"	"
Lake Cantara	Seed bank donor	-36.331644°	139.744104°	12 October 2021	"
	Non-donor	-36.329626°	139.748138°	"	"

Figure 13. Locations of sites where translocation works occurred from 2012-2014 and non-translocated sites for 2021 translocation evaluation surveys.

Figure 14. Location of the Lake Cantara seed bank donor site from 2012 and the non-donor site used for the 2021 seed bank donor site evaluation surveys.

Georeferenced locations (GPS coordinates) were used to ensure that sampling occurred within the areas where translocation works occurred following review and inspection of previous reports and consultation with DEW staff. To check that non-translocated sites were of similar composition to the translocated sites, we documented local conditions and checked that the sediment and environmental characteristics were similar (i.e. substrate not too rocky, similar sediment texture, similar water depths etc.).

At each site, we collected fifteen 75 mm core samples along three transects which ran parallel to the shoreline. Each transect was approximately 100 metres in length and was categorised by elevation/depth: ‘shallow’, ‘middle’ and ‘deep’. Transects were approximately 50 metres from the shore and at least 30 metres apart. The transects followed the methods used in the translocation works (Department of Environment and Heritage 2010), where three elevation/depth zones were determined in relation to the AHD (i.e. shallow, +0.2 – 0 m AHD; middle, -0.1 – -0.25 m AHD; and deep, -0.25 - -0.4 m AHD).

We also recorded location, water depth and algae presence and extent. Labelled samples were placed in calico bags returned to the laboratory and stored frozen until they were able to be processed.

Laboratory processing

In the laboratory, samples were defrosted from freezer storage, and sample numbers were cross-referenced with site data for quality control. Each individual sample was placed into a 500 µm sieve, and the sample bag was rinsed inside-out into the sieve to ensure all sample material was caught. The samples were then sieved to retain seeds and all plant material using mechanical action and running water. All sediment was collected for return to the Coorong to fulfil permit requirements.

Once thoroughly sieved, the material was rinsed and emptied into a plastic tray for further sorting. The tray was elevated on one side, and its contents spread across and up the tray such that seeds and plant biomass were separated from sediment. The contents of the tray were then inspected thoroughly. The first sample of each site was photographed pre- and post-sieving with its corresponding sample number for future reference. Seeds and turions contained within the samples were counted and recorded for resilience metrics.

Only plant material recognised as living prior to collection was included in counts and biomass estimates. This meant that the overall structure of the plant, i.e. rhizome, roots and shoots, was attached and present. Loose, unstructured and otherwise dead biomass was not included in data collection. Small aluminium foil containers were used for weighing biomass. These were labelled twice with their sample number for redundancy, and were subsequently weighed empty to five decimal places, so that dry aquatic macrophyte biomass could be determined following air drying (see below), then the wet weight was recorded.

Once all aquatic macrophyte biomass classified as living was collected, it was placed into the corresponding foil container and dried in the oven at 60°C for 48 hours. Once dry, the sample was weighed to five decimal places on a high precision balance. The original weight of the container was subtracted to determine the total dry weight of the sample, i.e. biomass (g DW), and this weight was recorded on the data sheet (again to five decimal places). The aluminium foil container was then tightly folded shut with the label clearly visible and stored in a vacuum-sealed bag among other biomass samples from the location for future analysis. Any seeds found were enclosed together in empty unused nylon teabags which were labelled with their corresponding sample number and sealed in a container with silica gel-based desiccant. This process was repeated for each core collected and the presence of samples and corresponding sample codes was also recorded.

Once finalised, data sheets were digitised, and their contents manually recorded in the project database. As data were entered, images of the laboratory data sheets were included in the database as a quality control cross checking measure. Other data quality assurance steps were also implemented, including a second data entry reviewer checking records to assist in identifying clerical errors or inconsistencies which were then rectified.

Statistical analysis

All data was analysed with IBM SPSS Statistics v. 28. We applied separate Multivariate Analysis of Variance (MANOVA) to analyse data from each survey; translocation condition, donor condition, translocation resilience and donor resilience as data sets were not fully compatible with each other. The condition surveys were focussed on collecting biomass data, while the resilience surveys focussed on seed banks and turion counts.

Wilks Lambda was used to assess the effects of factors on all variables. This was followed up with One-Way Analysis of Variance and Tukey's Honest Significant Difference (HSD) post-hoc test to test the effects of the individual factors (i.e. site, type of site and depth) on variables biomass, seed and turion counts m^{-2} where applicable.

To analyse data from the translocation versus non-translocated condition surveys we used the dependent variables; aquatic macrophyte biomass m^{-2}, *Ruppia* spp. seed count m^{-2}, and turion count (types I & II combined) m^{-2}, with fixed factors of; site, type of site (translocated, non-translocated) and water depth (shallow, middle, deep).

Data from the seed bank donor condition survey was analysed using the dependent variables; aquatic macrophyte biomass m^{-2} and turion count (types I & II) m^{-2}, with fixed factors of; type of site (seed bank donor and non-donor) and water depth (shallow, middle, deep). No seeds were found in this survey.

For the resilience surveys of translocated versus non-translocated sites, we used dependent variables; *Ruppia* spp. seed count m^{-2}, and turion count (types I & II) m^{-2}, with fixed factors of; site, type of site (translocated, non-translocated) and water depth (shallow, middle, deep).

The seed bank donor resilience survey used the dependent variables; seed count m^{-2} and turion count (types I & II) m^{-2}, with fixed factors of, type of site (seed bank donor and non-donor) and water depth (shallow, middle, deep).

2.2.2 Results

Condition of translocated sites

The overall effects of translocation were statistically significant when considering biomass, seed and turion counts ($F_{(3, 328)}$=15.869, p=<0.001, Wilks' Λ=0.873), suggesting that the results of the translocation works were still having an effect on the condition of the local Ruppia Community after 8 years.

Biomass was variable across sites, however, was higher overall where translocation had occurred (Table 4, Figure 15A). Although biomass was significantly higher at translocation sites than control sites, there was no significant difference between the three different water depths (Figure 16A) (F=0.300, p=0.741).

We found that there were significantly more seeds at translocation sites in the condition (June 2021) surveys, than at non-translocation sites (F=6.684, p=0.010), with a mean of 74.20 and 200.0 seeds m^{-2} in the non-translocated and translocated sites respectively. However, following the same trend as biomass, this did not differ with water depth (F=0.13, p=0.987) (Figure 16B).

Significantly higher numbers of turions were recorded at the translocated sites than where no translocation had occurred (F=30.50, p= <0.001) (Figure 16C). There was no significant difference between water depths (F=0.304, p= 0.738) (Figure 16C).

Table 4. Aquatic macrophyte biomass (g DW m^{-2}) descriptive statistics across all sites and overall. SD = standard deviation. N = number of samples.

SITE	TYPE OF SITE	MEAN BIOMASS (G DW/M^{-2})	SD	N
Woods Well	translocated	4.80	6.80	45
	non-translocated (control)	1.10	5.13	45
Fat Cattle Point	translocated	7.64	12.10	45
	non-translocated (control)	11.84	20.68	39
Jack Point	translocated	23.43	37.90	45
	non-translocated (control)	0.36	0.17	45
Policeman Point	translocated	8.80	10.16	45
	non-translocated (control)	8.98	19.66	45
Total	**translocated**	**11.17**	**21.85**	**180**
	non-translocated (control)	**5.27**	**14.97**	**174**
Lake Cantara	seed bank donor	91.10	37.23	45
	non-donor (control)	117.80	75.88	45

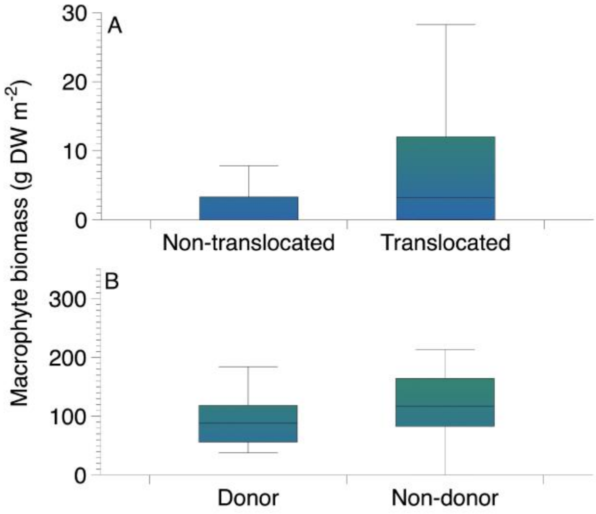

Figure 15. Aquatic macrophyte biomass m^{-2} box and whisker plots representing the Inner-Quartile-Range (IQR; lower value 25%, upper value 75%), mean, and 95% confidence interval (error bars). A. non-translocated (control) and translocated sites. B. Lake Cantara seed bank donor and non-donor (control) sites. Note different y-axes. Survey dates 15-16 June 2021.

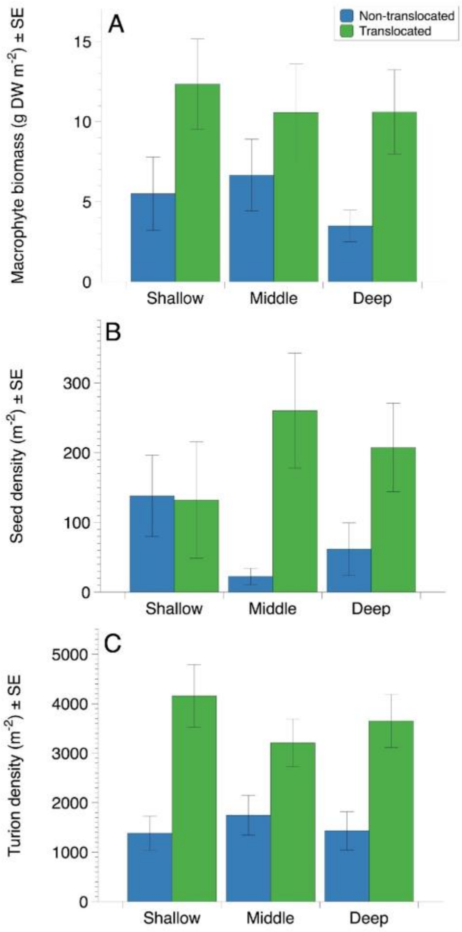

Figure 16. Results per depth range for the condition surveys at translocated and non-translocated (control) sites, 15-16 June 2021 for A. Mean aquatic macrophyte biomass (g DW m^{-2}) ± s.e. B. Mean *Ruppia* sp. Seed counts m^{-2} ± s.e. C. Mean Ruppia turion counts m^{-2} ± s.e. Depths surveyed; shallow, +0.2 – 0 m AHD; middle, -0.1 – -0.25 m AHD; and deep, -0.25 - -0.4 m AHD. Survey dates 15-16 June 2021.

Condition of donor site

The effects of the seed bank extraction works were still detectable at Lake Cantara when assessing condition at the donor site ($F_{(2,83)}$=3.64, p=0.36, Wilk's Λ=0.923). There was significantly less biomass within the donor site than at the non-donor site where no works occurred, with means of 91.10 and 117.80 g DW m^{-2} respectively (F=4.928, p=0.029) (Figure 15B). Biomass varied between water depths with significantly higher biomass in the non-donor deep water transect than in any other Lake Cantara depth transect (F=5.890, p=0.004) (Figure 17A).

There was no significant difference in turion counts between donor and non-donor sites (F=1.267, p=0.264) or at different depths (F=0.522, p=0.595) (Figure 17B). No seeds were present in samples collected during the seed bank donor site condition survey.

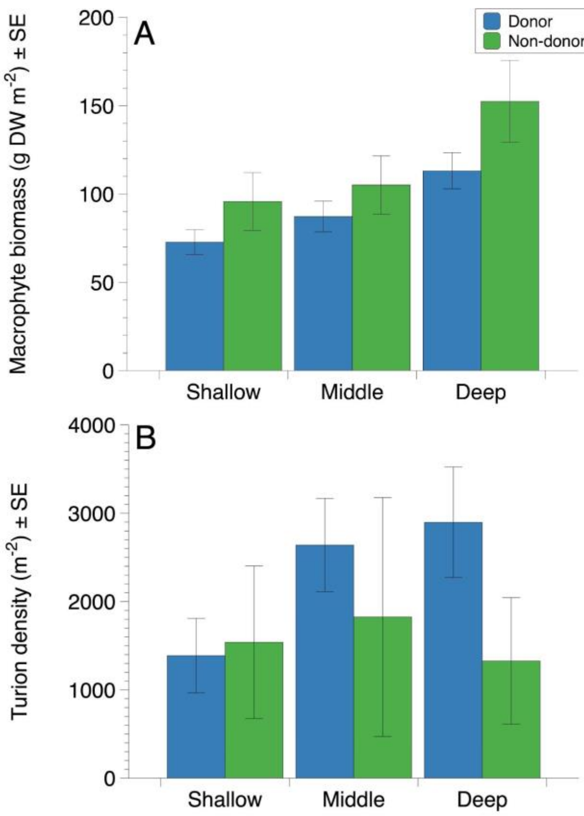

Figure 17. Results per depth range for the condition surveys (Table 3) at seed bank donor and non-donor (control) sites for; A. Mean aquatic macrophyte biomass (g DW m^{-2}) ± s.e. B. Mean Ruppia turion counts m^{-2} ± s.e. (note turions are in the forming stage at this time of year and were not completely formed). No Ruppia seeds were found in cores during this survey so are not reported. Depths surveyed; shallow, +0.2 – 0 m AHD; middle, -0.1 – -0.25 m AHD; and deep, -0.25 - -0.4 m AHD. Survey date 12 October 2021.

Resilience of translocated sites

During the resilience surveys conducted in March 2022, seed numbers were very low, while turion numbers were high (Figure 18), a result which is consistent with Lewis et al. (2022). There was no overall significant difference in resilience (seed and turion counts) m^{-2} within the translocated and non-translocated sites ($F_{(3, 325)}$=3.014, p=0.050, Wilks' Λ=0.982) or water depth ($F_{(4, 650)}$=1.253, p=0.287, Wilks' Λ=0.985).

There were significantly higher seed counts at the non-translocated sites when compared with the translocation sites with means of 35.33 and 2.6 seeds m^{-2} respectively (F=0=5.862, p=0.016), however there was no significant difference between water depths (F=0.522, p=0.595) (Figure 18A).

There was no significant difference between turion counts at translocation or non-translocation sites, with means of 6617 and 6708 m^{-2} respectively (F=0.207, p=0.649), or between water depths (F=0.123, p=0.884) (Figure 18B).

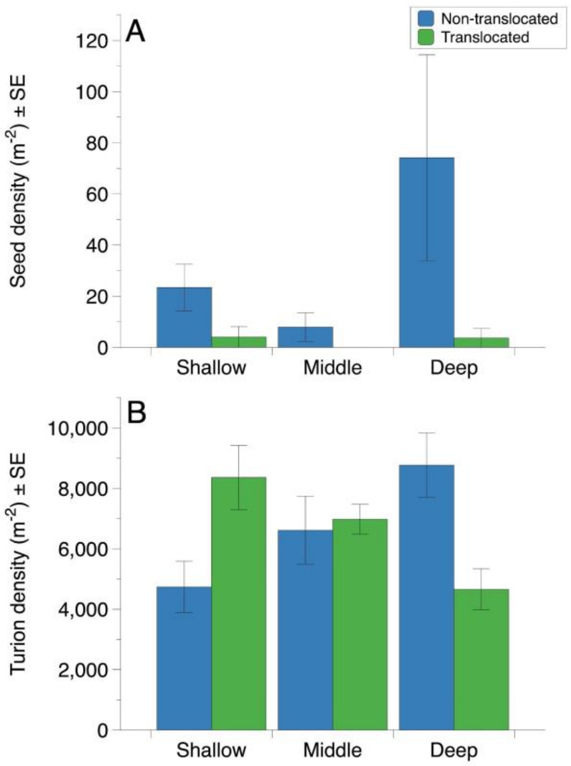

Figure 18. Results per depth range for the resilience surveys at translocated and non-translocated (control) sites, 16 March 2022 for A. Mean Ruppia seed counts m^{-2} ± s.e. and B. Mean Ruppia turion counts m^{-2} ± s.e. Depths surveyed; shallow, +0.2 – 0 m AHD; middle, -0.1 – -0.25 m AHD; and deep, -0.25 - -0.4 m AHD. Survey date 16 March 2021.

Resilience of donor site

Overall, there was a significant difference in resilience (seed and turion counts) between the seed bank donor site and non-donor site ($F_{(2, 83)}$=21.094, p=<0.001, Wilks' Λ=0.663) and between water depths ($F_{(4, 166)}$=3.543, p=<0.008, Wilks' Λ=0.849) (Figure 19).

There was significantly lower seed density found at the seed bank donor site, than at the non-donor site (F=23.756, p=<0.001) with overall means of 25.20 m^{-2} found within the donor site and 950.7 m^{-2} at the non-donor site. This trend was also seen in turion counts with 16,770 and 32,026 m^{-2} found at the donor and non-donor sites respectively (F=28.360, p=<0.001). Seeds density also differed significantly across water depths (F=3.415, p=0.038) with Tukey's HSD indicating that there was significantly less seeds in the deep transects (p=<0.05) (Figure 19A). Turion counts m^{-2} did not differ significantly across water depths (F=0.123, p=0.884) (Figure 19).

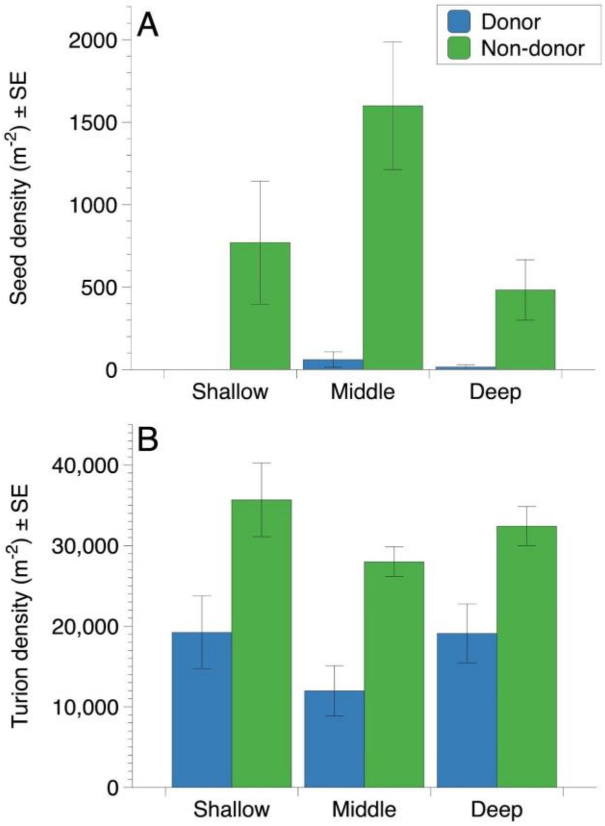

Figure 19. Results per depth range for the seed bank donor site resilience surveys at donor and non-donor (control) sites, 24 March 2022 for A. Mean Biomass m^{-2} ± s.e. and B. Mean turion counts m^{-2} ± s.e. Depths surveyed; Shallow, +0.2 – 0 m AHD; middle, -0.1 – -0.25 m AHD; and deep, -0.25 - -0.4 m AHD. Survey date 24 March 2021.

2.2.3 Discussion

Overall, this study suggests that after nearly 10 years, translocation of seed laden sediments from Lake Cantara had a positive effect on the Ruppia Community at direct translocation sites in the southern Coorong. Specifically, the condition of plants, measured as change in biomass m^{-2}, was higher at translocation sites than non-translocation sites. During the condition (June) survey, conducted during the Ruppia Community vegetative growth period, resilience, measured as seed and turion counts m^{-2}, was also significantly higher at the translocation sites. In contrast, low seed and high turion counts were observed in the resilience survey undertaken during the period of aestivation during low water levels in summer, however there was not a significant difference in resilience overall between the translocated and non-translocated sites.

The Ruppia Community experienced a shift in reproductive strategy during the course of this study from seed production to turion formation, likely due to environmental conditions (Lewis et al. 2022). This was reflected in the differences between seed and turion production in the condition (2021) and resilience (2022) surveys. To counter this, we focussed on overall resilience rather than seeds or turions individually. Resilience based on turion production is relatively ephemeral, only applying to survival from one growing season and another (Brock 1982). As a result, long-term resilience, in the context of the long-term ability of sites to recover following poor seasonal conditions, as experienced during the Millennium Drought, was poor in 2020-21 season. The robust seed bank detected during the condition survey reflect reproductive effort from the season before. These factors should also be considered when planning translocation works, as depending on the timing of the works, low seed counts could affect the effectiveness of translocation.

Eight years post translocation the donor site, Lake Cantara, showed reduced biomass when compared with the non-donor site. However, we also observed that, overall, biomass at the seed bank donor site was 3.8 times higher than the highest mean biomass measured in the southern Coorong (Jack Point, translocated).

There was a 22% lower mean biomass at the seed bank donor site in comparison to the non-donor site. Field observations from the survey noted that along transects at the non-donor site, there were large masses of *Althenia cylindrocarpa* flowers, which may have accounted for some of the variation in biomass. While the two sites appeared similar environmentally and geographically, natural variation such as species composition may have had some influence on the outcomes.

Interestingly, during the seed bank donor site condition survey, no viable *Ruppia* spp. seeds were found in samples from the donor or non-donor sites. Given the high Ruppia Community biomass we observed, it may suggest that there is high germination success in Lake Cantara while it appears to be lower in the southern Coorong where un-germinated seeds were present. Kautsky (1990) also found that there was little correlation between biomass and seed counts in aquatic macrophytes.

Site selection for future translocation works should meet the Ruppia Community habitat requirements detailed in (Lewis et al. 2022). To determine the habitat suitability of proposed translocation sites, it is recommended that sediment condition, expected algal biomass and the biomass of the existing Ruppia Community is assessed. Given the resilience of the Ruppia Community, it is likely that if there is no past evidence of Ruppia Community being present at a site, it is less likely to be successful as a restoration site (White and Walker 1997, Tan et al. 2020). Timing of restoration works within the Coorong is also critical, and minimising stressors which might impact the success of *Ruppia* translocation will maximise efficacy and minimise associated costs (Neeson et al. 2016).

At the time of the surveys, no filamentous algae was present at any sites, therefore algal biomass was not factored into the experimental design of this study. However, the presence of filamentous algal mats should be taken into account when selecting sites for future translocation works as it could affect long-term outcomes.

3 Principles for restoration of the Ruppia Community in the southern Coorong

3.1 Introduction

Recovery of complex ecosystems, such as the Coorong, from the changes caused by long-term and cumulative change, will involve similar or longer recovery timelines. Actions that aim to support the recovery of ecological processes should be applied to the appropriate stage of the restorative continuum leading to the long-term outcomes set as targets (Diefenderfer et al. 2021, SERA 2021b). Conditions in the Coorong South Lagoon during winter 2020 to summer 2021 have shown an increase in the distribution of Ruppia Community (Paton et al. 2020, Waycott et al. 2020b, Lewis et al. 2022) continuing the long-term trajectory of post-Millennium Drought recovery of the Ruppia Community. The widespread distribution in 2021 of this recovering Ruppia Community appears to be following a model typical of rapid, or even exponential, population growth. Earlier stages of recovery were slow with fewer, more isolated populations of patchy, low plant densities. Later stages of recovery were more rapid as higher densities in local populations led to increased seed banks and subsequent increased population expansion rates. These timelines for recovery provide a reference for future expectations, although it should be noted that recovery has been impeded by poor water quality (Collier et al. 2017, Paton et al. 2020, Waycott et al. 2020a) and seasonal availability of adequate water levels to complete the lifecycle of the aquatic macrophytes present in the existing Ruppia Community (e.g. Figure 12).

Reasonable expectations for recovery timeframes and magnitudes associated with restoration actions need to be set, especially in a variable and highly constrained environment such as the Coorong. For example, the recovery of the Ruppia Community at translocation sites following the Millennium Drought was slower than expected, with the target of eight seeds per core not met in the 2–3 seasons monitored (Figure 11). As a result, novel approaches to improving outcomes for ecosystem restoration overall were explored. To support decision making for Coorong ecosystem restoration a model was developed, the Ruppia HSI (Ruppia Habitat Suitability Index), to estimate habitat suitability for the Ruppia Community in the southern Coorong (Collier et al. 2017, Hipsey et al. 2020, Hipsey et al. 2022). Model development identified several significant knowledge gaps which informed priority research undertaken in the Healthy Coorong, Healthy Basin Trials and Investigations project.

The Restoration Strategy outlined here provides an approach to developing restoration options fit for implementation. Restoration options developed are based on the state of the Ruppia Community, the stressors influencing its condition and the scale of impact likely to be experienced. We also discuss the implications of different environmental conditions applicable to restoration options.

3.1.1 Ecological restoration principles and evaluating success

“A proposal for restoration of any ecosystem or particular environment presupposes that the system has been in some way anthropogenically degraded, whether deliberately, accidentally or even through well-intentioned management actions. Active restoration in turn implies a recognition, based on valid criteria, of an unnatural degraded state, the loss of a natural resource and the level of significance of such a loss on a regional, national and even global scale.” (Forbes et al. 2020).

Ecological restoration is an activity which initiates or accelerates the health, integrity and sustainability of an ecosystem (Clewell et al. 2004). Understanding how biotic variables, such as aquatic macrophyte communities, respond to changing abiotic or environmental variables is critical to achieving ecological restoration outcomes (Taylor et al. 2006). Restoration can be differentiated from rehabilitation activities as it involves active intervention, rather than relying on natural recolonisation (Tan et al. 2020). It is preferable for wild or indigenous ecosystems to be on a trajectory where they can be maintained without needing intervention once restoration targets are achieved. In fact, where possible ecosystems should have attributes that match those of an appropriate reference community or a detailed understanding of the ecological components, processes and services that have been used to establish targets for a desired state.

The Society for Ecological Restoration Australasia (SERA) have established standards that are based on regionally relevant practical and tested principles that inform ecological restoration actions (McDonald et al. 2016, SERA 2021b). The guidelines contain an assumption that a recognised end-point or target has been identified as the desired state enabling key principles and attributes to be assessed during the development of restoration strategies or evaluating their outcomes (Table 5, Table 6) (SERA 2021b). The SERA principles have a strong focus on using an indigenous or native reference site, to act as a guide for the restoration of an ecological community however, we suggest this is unachievable for the Coorong due to a lack of such sites.

Table 5. The six key principles of ecological restoration practice as outlined in SERA (2021b).

Key principles of Restoration Practice	
1	Ecological restoration practice is based on an appropriate local native reference
2	Restoration inputs will be dictated by level of resilience and degradation
3	Recovery of ecosystem attributes is facilitated by identifying clear targets, goals and objectives
4	The goal of ecological restoration is full recovery, insofar as possible, even if outcomes take long timeframes or involve high outputs
5	Restoration science and practice are synergistic
6	Social aspects are critical to successful ecological restoration

Table 6. The six key attributes of ecological restoration practice as outlined in SERA (2021b).

KEY ATTRIBUTES OF RESTORATION PRACTICE	
Absence of threats	Direct degradation drivers (e.g. overutilization, contamination inputs, sources of invasive species) are minimal or effectively absent.
Physical conditions	Environmental conditions (including the physical and chemical conditions of soil, water, and topography) required to sustain the ecosystem are present.
Species composition	The native species characteristic of the appropriate ecosystem are present, whereas invasive species are minimal or effectively absent.
Structural diversity	Appropriate diversity of key structural components, including demographic stages, faunal trophic levels, vegetation strata, and spatial diversity are present.
Ecosystem function	Appropriate levels of growth and productivity, nutrient cycling, decomposition, habitat, species interactions, and types and rates of disturbance are present.
External exchanges	The ecosystem is appropriately integrated into its larger landscape or aquatic context through positive abiotic and biotic flows and exchanges.

The Coorong ecosystem is unique for many key attributes that, at least in part, contributed to the original listing of the Ramsar site (Department of Environment 2013). The Coorong, as a long and narrow estuary at the end of the Murray–Darling Basin system is at the junction of the River Murray and the Southern Ocean. The extreme area of the Murray–Darling Basin catchment, more than 1 million km^2, makes the Coorong critically important as it is the conduit for removing salt, sediment, nutrients and pollutants from the Basin and for species that require fresh and salt water to complete their life cycle. However, this also creates a unique hydrological and physical environment and the biota that have adapted to life under these conditions, all part of why the Coorong estuary is a special place.

Some of these unique attributes will influence options available to ecological restoration practice (Table 6) including local and regional physical conditions, and external exchanges (Department for Environment and Water 2022b). Therefore to achieve the proposed desired state (Department for Environment and Water 2021c) some or all of these attributes may need to be modified to restore conditions enabling restoration. Another significant challenge will be the adoption of strategies that will work under the highly variable environmental conditions such as, changes in the abiotic factors or the physical environment which have the potential to make conditions unfavourable or alternatively improve the environmental conditions for the biota. There will be knowledge gaps that emerge to address managing this variability to achieve outcomes that lead to highly a productive and resilient Ruppia Community (e.g. high biomass plants in Figure 20).

3.1.2 Desired state for the Ruppia Community

Using the principles of SERA (2021b), along with the current knowledge base of the southern Coorong, as summarised in preceding chapters of this report, we present a strategy for restoration of the Ruppia Community. The strategy includes recognition that intervention actions to achieve ecological restoration operate as a cycle that iteratively progresses towards the long-term goal of improving the ecological health of the Coorong (Figure 21).

The objective of the Restoration Strategy is to restore a resilient Ruppia Community that supports diverse ecological function in the southern Coorong. The objective can be framed as a desired outcome state:

'A resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions'

Key elements of monitoring the progress of any restoration actions, should be to provide evidence of the trajectory towards the desired state, including attributes associated with the biota itself. Thus, a focus on the Ruppia Community, physical environment, hydrological conditions, physical disturbances (such as sediment disruption) and the chemical environment (including inorganic and organic nutrients) is essential. To achieve effective monitoring, establishing the 'reference condition' followed by the evaluation of monitored attributes will provide evidence of the trajectory of the system and a clear vision of an outcome, (e.g. production of a dense, higher biomass Ruppia Community to provide a food source and habitat, as well as slow nutrient cycling and reduce availability within the Coorong system, Figure 20).

Figure 20. Dense Ruppia Community (*Ruppia tuberosa*, *Ruppia megacarpa* and *Althenia cylindrocarpa* growing inter-mixed) flowering in a small lagoon adjacent to the main Coorong waterway (near Parnka Point, Central Coorong). Scale: the width of the image is ~1 m across and water was approximately 30 cm deep, photograph taken in November 2016 by M. Waycott.

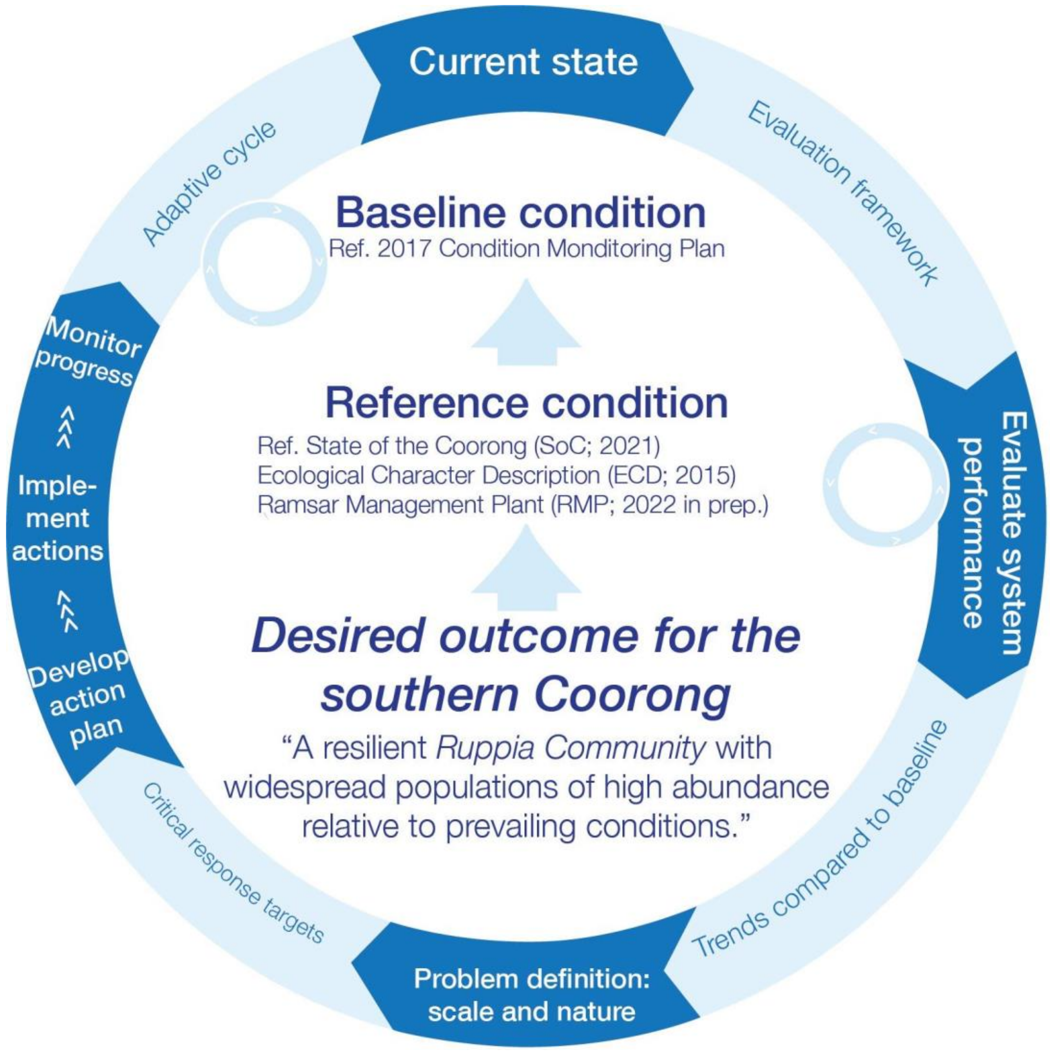

Figure 21. Model for a southern Coorong Ruppia Community restoration cycle where iterations are based on an evaluation of the progress the current state of the system has made towards long-term targets. The stages of actions (dark blue) are linked by the objectives to be implemented to achieve outcomes (light blue).

3.1.3 Reference condition for the Ruppia Community

The current reference condition for Ruppia Community in the Coorong is defined by several key policy documents:

- Long-term Watering Plan (Department for Environment and Water 2020a)
- Ramsar Management Plan (Department for Environment and Water 2021a)
- Ecological Character Description (ECD) of the Coorong and Lakes Alexandrina and Albert (Department for Environment and Water 2021b), including a *Ruppia tuberosa* specific report (Paton et al. 2015b)
- Condition Monitoring Plan (Department for Environment and Water and Natural Resources 2017) for The Living Murray initiative.

It is worth noting that these documents and ongoing reports refer to *Ruppia tuberosa* as equivalent to the Ruppia Community in most cases. Many of these policies are in the process of review and are planned to be updated following the completion of the Healthy Coorong, Healthy Basin program in 2022 and incorporate outcomes of reviews of the progress of key attributes in the Murray–Darling Basin Plan (e.g. Department for Environment and Water 2020b).

A significant challenge for managing the restoration of the Coorong, like other high variability and extreme ecological systems, is that establishing a reference condition may not be able to take into account the effects of multiple stressors within a system (Atkinson et al. 2022). The complexity of the Coorong ecosystem, including its extreme chemical (nutrients and salinity) gradient, connection to the river and ocean, and flow constrictions along its length, mean that there are no comparable reference systems. Baseline condition targets currently have been established to reflect what is known of pre-drought abundance and distribution (Paton and Bailey 2010, Paton et al. 2011) and these have been discussed in the 2020 review of the assessment of environmental outcomes (Department for Environment and Water 2020b).

Given the current state of the Ruppia Community in the southern Coorong, as described by Lewis et al. (2022), there is a need to review the ecological change and recovery following the Millennium Drought and incorporate new research such as the outcomes of Healthy Coorong, Healthy Basin program. Alternative options and targets for evaluating the state of the Coorong ecosystem are being developed and these are informed by the Trials and Investigations research activities of the Healthy Coorong, Healthy Basin program (Department for Environment and Water 2022e).

3.2 Lessons learned from previous Coorong Ruppia Community restoration actions

Approaches to developing restoration actions can be usefully informed by lessons learned from previous work completed to restore the loss of ecological function in a system (Tan et al. 2020, Schulz-Zunkel et al. 2022). The loss of the Ruppia Community during the Millennium Drought over the period of 2000–2010 resulted from unprecedented conditions across an unusually large scale of impact encapsulating the Coorong. The Millennium Drought represented the worst drought and one of the driest periods recorded across south-eastern Australia over the last 200+ years (see chapter 1). As a result, the lessons learned are particularly significant in that they represent extreme conditions leading to almost complete loss of the aquatic macrophytes in the Coorong as a whole. The loss of the Ruppia Community from the Coorong South Lagoon and southern area of the Coorong North Lagoon during the Millennium Drought (Table 7) provides a knowledge base for two different intervention scenarios at different times since the loss occurred. First, *Ruppia tuberosa* translocations to restore the presence in the Coorong post drought. Second, management of ongoing risks to the Coorong ecosystem has led to a need for a broader scale of potential interventions to restore critical ecological functions (Brookes et al. 2018, Department for Environment and Water 2018, 2019, 2022d).

In Table 7 the stages of the southern Coorong Ruppia Community restoration cycle (Figure 21) are used to summarise the potential outcomes of restoration decision making processes. A range of options were investigated for recovering *Ruppia tuberosa* in the Coorong South Lagoon at the end of the drought (Department of Environment and Heritage 2010). Following these investigations, a seed-based translocation program, conducted over two seasons in 2012-13 and 2013-14, was successful at establishing local populations of a Ruppia Community as described in Chapter 2 of this report. However, there was not a rapid recovery of a resilient seed bank (>2,000 seeds m^{-2}) in the two seasons of monitoring following the translocation actions (Paton et al. 2015b) (Figure 11). More recent surveys (Chapter 2 this report, Lewis et al. 2022) and ongoing monitoring (Paton et al. 2021) across the Coorong establish that seed bank recovery might not be expected to reach this level in only a few seasons, but population density of reproductive individuals is an important consideration for the generation of higher seed densities.

In the season following the seed translocation actions, ongoing concerns about the state of the Coorong ecosystem led to a review of the options for improving the ecological health of the system. This review was based on ongoing monitoring of southern Coorong water quality (Stone et al. 2016, Mosley and Hipsey 2019), biota (Dittmann et al. 2017, Paton et al. 2017b, a, Ye et al. 2018) and community consultation (Department for Environment and Water 2018). In addition, an expert scientific panel was convened to provide advice to the community consultation process, government decision makers and managers and to present the evidence base on the current state of knowledge of Coorong ecological health and identify critical knowledge gaps (Brookes et al. 2018). The outcome of these activities was the formation of the Healthy Coorong, Healthy

Basin program and a priority activity has been to act on the evidence from these reviews that several components, processes and services critical to the ecological character of the Coorong were at risk of exceeding their limits of acceptable change. Priority research was identified to investigate options to reverse the presence of algal blooms in summer causing impacts on the reproduction of aquatic plants and degrading the quality of mudflats on which migratory shorebirds forage (Department for Environment and Water 2019).

The activation of the program to investigate large scale restoration options (Table 7 summarised in 2020 column) included a basis that recognised the condition of the southern Coorong as hyper-eutrophic with limited options to reverse this under current conditions. With specific reference to the Ruppia Community, ongoing hyper-eutrophic conditions were resulting in heavy algal loads in the system (e.g. Figure 25), reducing water clarity and enabling filamentous algal blooms to proliferate (Collier et al. 2017, Asanopoulos and Waycott 2020, Mosley et al. 2020, Paton et al. 2021). The need to shift the system from a hyper-eutrophic to mesotrophic state (Department for Environment and Water 2021c) was highlighted as critical and has been included as an essential element of the evaluation of options to deliver restoration outcomes (Department for Environment and Water 2022b). In fact, the need to remediate salt and nutrient loads is critical to considering further direct action in restoring biota, including improving the resilience of the Ruppia Community in the southern Coorong into the future.

Table 7. Features of the Ruppia Community for developing actions following the restoration cycle proposed to be adopted for the southern Coorong. Two exemplars are considered, 2010 representing the end of the Millennium Drought, and 2020 representing the initiation of the Healthy Coorong, Healthy Basin program.

	2010	2020
Current state	Ruppia absent from system [1]	Algal blooms, conditions leading to anoxic sediments and high organic matter in populations and poor reproductive success [3,4,5,6]
Evaluation	Critical component of the system absent (Ruppia Community), significant risk to the ongoing ecological character of the Coorong ecosystem indicated [2]	Hyper-eutrophic state persisting, consequences include loss of Ruppia Community fitness due to interference by filamentous algal blooms with completion of lifecycle [2,3], high microalgal loads leading to sediment condition deterioration [5], nutrient cycles disrupted, significant risk to the ongoing ecological character of the Coorong ecosystem indicated [5]
System performance compared to baseline	System degraded and Ruppia Community scarce with low (zero) resilience and poor condition [1,2,3]	Ruppia Community widely distributed and greater than pre-drought extent and density but adversely impacted by algal blooms and poor water and sediment quality [6]
Scale and nature of problem	Widespread loss of Ruppia Community across the southern Coorong [1,2,3]	Whole of system experiencing hyper-eutrophic conditions [5]
Action Plan	Intervention to recover the Ruppia Community via seed translocation (Chapter 2) [1,11]	Evaluating interventions to reduce nutrient loads in whole system before Ruppia Community restoration interventions implemented
Implementation	Direct intervention through translocation of seed laden sediments from nearby site with similar attributes and pilot study undertaken [7]	Developing whole of system recovery options to permanently restore the system to a desired state including large scale infrastructure [8,9]. Restoration actions proposed to be implemented with infrastructure options [7]
Monitoring	Ongoing widespread monitoring by The Living Murray (TLM) program [10] but inconsistent monitoring since translocation of sites where actions occurred [11]	TLM monitoring ongoing across Coorong and Healthy Coorong, Healthy Basin Trials and Investigation program [6]
Outcome (s)	Positive outcomes from 2012-2014 seed translocations, can only document localised impact due to lack of monitoring data of the restoration sites and relevant reference sites. It is possible local sites increased the rate of colonisation by their early recovery	Broad scale recovery of some biota following Millennium Drought, widespread poor conditions in the system documented. Planning for removal of the pressures associated with eutrophication and poor connectivity. Next steps for direct ecological restoration actions identified and development of a monitoring program to meet system needs underway

Citations: Paton and Bailey (2010)[1], Paton et al. (2017b)[2], Collier et al. (2017)[3], Brookes et al. (2018)[4], Mosley and Hipsey (2019)[5], Lewis et al. (2022)[6], Department of Environment Water and Natural Resources (2014a)[7], Department for Environment and Water (2022c)[8], Department for Environment and Water (2022b)[9], Murray–Darling Basin Authority (2022)[10], this study[11].

4 Restoration strategy for the Ruppia Community in the Southern Coorong

4.1 Overview

The desired state for the Ruppia Community in the southern Coorong is to restore *‘A resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions’*.

The re-establishment of a highly resilient Ruppia Community would provide diverse ecological functions to the Coorong ecosystem including:

- the provision of food and habitat for other species including fish and birds,
- sediment stabilisation reducing turbidity and erosion,
- sequestration of nutrients (carbon, nitrogen and phosphorous) leading to longer nutrient turnover cycles and supporting food webs, and
- recognising and maintaining these highly adapted aquatic macrophytes which have intrinsic value as species of remarkable evolutionary significance.

This strategy establishes aims to support the effective protection and conservation of the Ruppia Community and identify pathways to restore the natural values and ecological functions essential for a healthy and productive aquatic macrophyte community. This strategy is bespoke to the exceptional and unique environment of the Coorong, in particular the southern Coorong. No equivalent indigenous reference system is available for developing targets, and the management of the Coorong ecosystem is based upon the Ramsar Management Plan (Department for Environment and Water 2021a) and associated documents (see Section 3.2).

4.1.1 Objectives

This strategy aims to support the ongoing management of the aquatic macrophyte community in the southern Coorong recognising it as a critical component of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar site. To achieve this, pressures that impact the Ruppia Community will need to be addressed. This will lead to specific actions to be undertaken that protect, maintain, and improve the Ruppia Community ultimately seeking to restore the ecological community to its desired state. The objectives of this strategy are to:

1. Provide a strategy that supports conservation outcomes, protection of the interconnected natural, First Nations Partnerships team and community values for the Ramsar site, informs management actions and community initiatives that restore *‘A resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions’*. This objective should be to achieve the best possible outcome based on our knowledge of the system (e.g. Figure 24).
2. Summarise the current needs for protecting and conserving the Ruppia Community of the southern Coorong including known and expected threats to the ongoing presence of the community (e.g. Figure 22).
3. Outline a process to facilitate the incorporation of management actions and monitoring activities following the proposed southern Coorong Ruppia Community restoration cycle (as presented in Figure 21) including the following workflow (Figure 26, numbers correspond to those in the figure):
    1. **Define** the desired outcome.
    2. **Establish** the reference condition for the southern Coorong Ruppia Community.
    3. **Develop** the baseline condition that enables evaluation of indicators against the reference condition and proposed long-term trends (trajectory) towards achieving the desired state.
    4. **Describe** the current state of the Ruppia Community based on measured indicators.
    5. **Evaluate** the current state compared to the baseline condition and establish the trajectory towards targets, including an assessment of Ruppia Community resilience.

6. **Identify** the problem and potential intervention options based on outcomes of the evaluation.
7. **Decide** on intervention options:
   A. no intervention
   B. intervention including scale dependent considerations.
8. **Monitor** progress and feed into adaptive cycle to achieve outcomes.

4. Identify factors that may limit achieving restoration outcomes, including:
   - Scales of interdependencies including spatial and temporal scales of impacts and the associated restoration options (i.e. Table 8).
   - Known ecological interdependencies including Ruppia Community life-history considerations and population recovery trajectories.
   - Considerations for intervention actions (propagule sources (seeds) and donor), population considerations (population size, genetic factors and recovery timelines) and critical knowledge gaps (evaluation of the likely impacts of climate change and changing land use in catchments surrounding the Coorong).

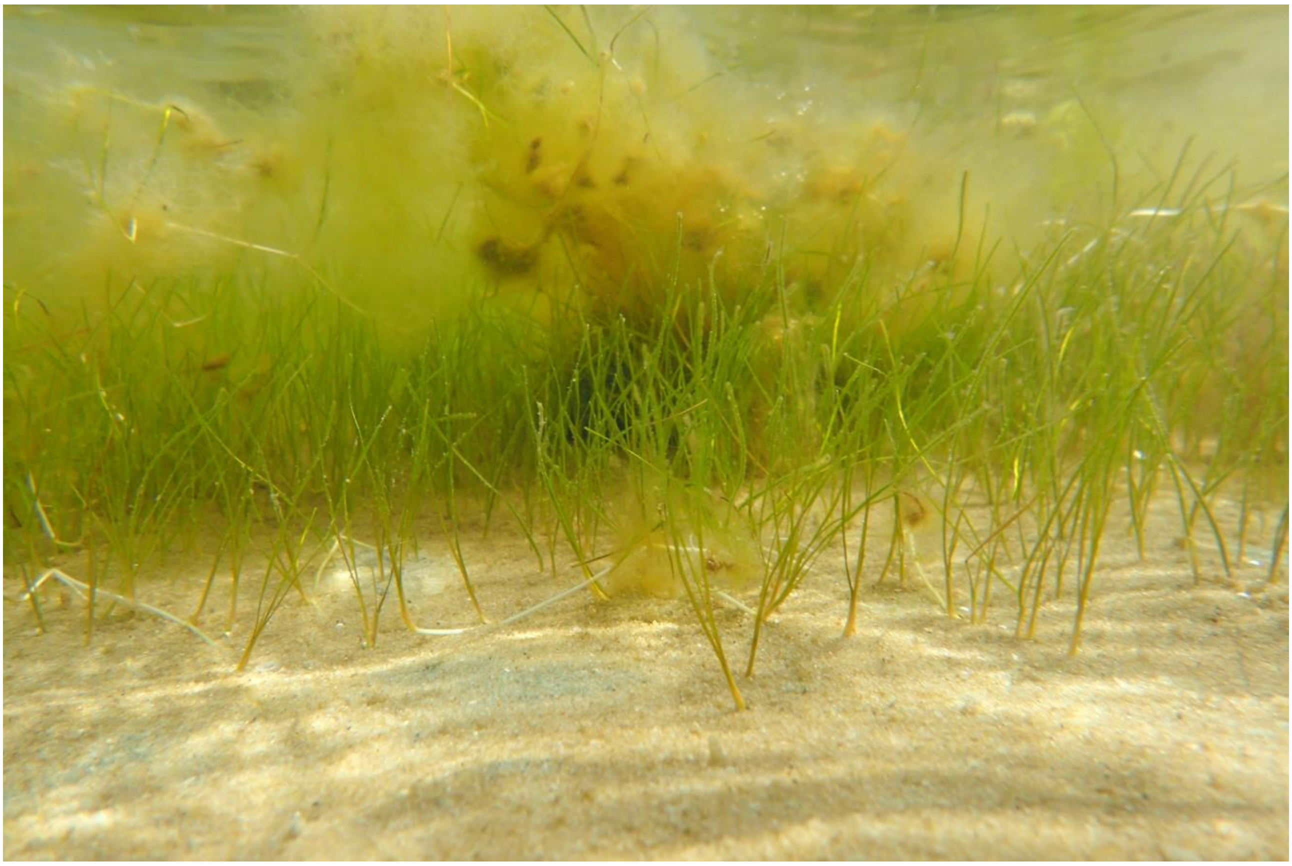

Figure 22. Mixed species Ruppia Community in the Coorong south of the Noonameena National Parks offices, 2 November 2021. Leaf length of plants ~1—15 cm. Note colonising growth form with rhizomes (white horizontal stems) visible at the edge of the meadow, filamentous algal tufts already attaching to new plant structures and a larger clump of algae with plants caught above the main canopy. Underwater photograph by Ryan Lewis.

4.1.3 Approach

The following sections of the strategy directly present the major objectives in separate sections. Each section has examples drawn from the lessons learned (Table 7) along with summaries and tools developed for application to this strategy. The final section provides a summary of proposed next steps for integrating this detailed Restoration Strategy for a keystone element of the Coorong ecosystem with an overall Coorong Restoration Strategy.

4.2 Supporting conservation outcomes, protection of values and management actions leading to a resilient Ruppia Community

4.2.1 Coorong and Lakes Alexandrina and Albert Wetland Ramsar site

The Coorong and Lakes Alexandrina and Albert Wetland Ramsar site covers more than 140,000 ha (Department of Environment 2013). The Coorong is a more than 100 km long estuary, inverse at the southern end, and forms a significant component of the Ramsar site (Department of Environment and Heritage 2000). As already described, change to the ecological character of the Coorong has occurred during the Millennium Drought, leading to a shared concern by community and managers for its health (Department of Environment 2013). Synthesis of the state of the system and the provision of scientific advice (Brookes et al. 2018) confirmed these concerns and an action plan to improve the health of the Coorong was developed (Department for Environment and Water 2019). The importance of the Ruppia Community was recognised in these reviews and the maintenance of a healthy Ruppia Community continues as an important component supporting maintenance of the values of the Ramsar site.

4.2.2 Active community engagement

The initiation of the Healthy Coorong, Healthy Basin program incorporated proactive engagement with broad community input to the development of solutions. The establishment of the Coorong Partnership group enabled experience and knowledge of local community and First Nations individuals to input directly into the options development for restoring the health of the Coorong (Department for Environment and Water 2022a). Consultation, with the wider community was able to deliver scientific evidence and a synthesis describing the current state of the Coorong, explain options for rehabilitating and restoring the Coorong system and reduce uncertainty associated with the next steps through active engagement (Figure 23).

Figure 23. Coorong BioBlitz, 21 May 2021, at Parnka Point, community members engaged in observing the Ruppia Community and threats to Coorong ecological functions due to algal blooms. Photograph by Emma O'Loughlin.

Community feedback indicated they highly valued the active engagement and the consultation process and the following summary statement from one series of workshops supported the role of science in the program:

> "Options for improving the ecology of the South Lagoon should be determined by scientific evidence, given water availability and constraints." (Department for Environment and Water 2022a).

The community has been directly involved in this project, investigating Plants and Algae of the southern Coorong (Department for Environment and Water 2022e). Participation included field work, workshops, seminars and face to face small group discussion sessions as well as sharing resources such as photographs and local knowledge. In particular, local knowledge assisted in identifying areas of high filamentous algal biomass and led to improved assessment of areas not typically accessed which has improved scientific outcomes (Lewis et al. 2022). This strong community involvement led to enhanced understanding of the system based on local knowledge and has been used to inform the development of this restoration strategy.

There would be value in future programs to engage with the community, including increased exposure to scientific investigations that will improve understanding of technical, social and practical issues among scientists, managers and members of the public. Active participation of community members and interest groups can lead to working with an increased knowledge base and positive community participant experience and should be an essential part of project development.

4.2.3 Changing states of the southern Coorong Ruppia Community

The objective of the Restoration Strategy is to restore a resilient Ruppia Community that supports diverse ecological functions. More specifically, to achieve this '*widespread populations of high abundance relative to prevailing conditions'* are to be restored (this report Section 3.2). Conceptually, achieving the desired state should see the return of healthy ecological functions, depicted as a historic state below (Figure 24) and discussed in the State of the Southern Coorong discussion paper (Department for Environment and Water 2021c).

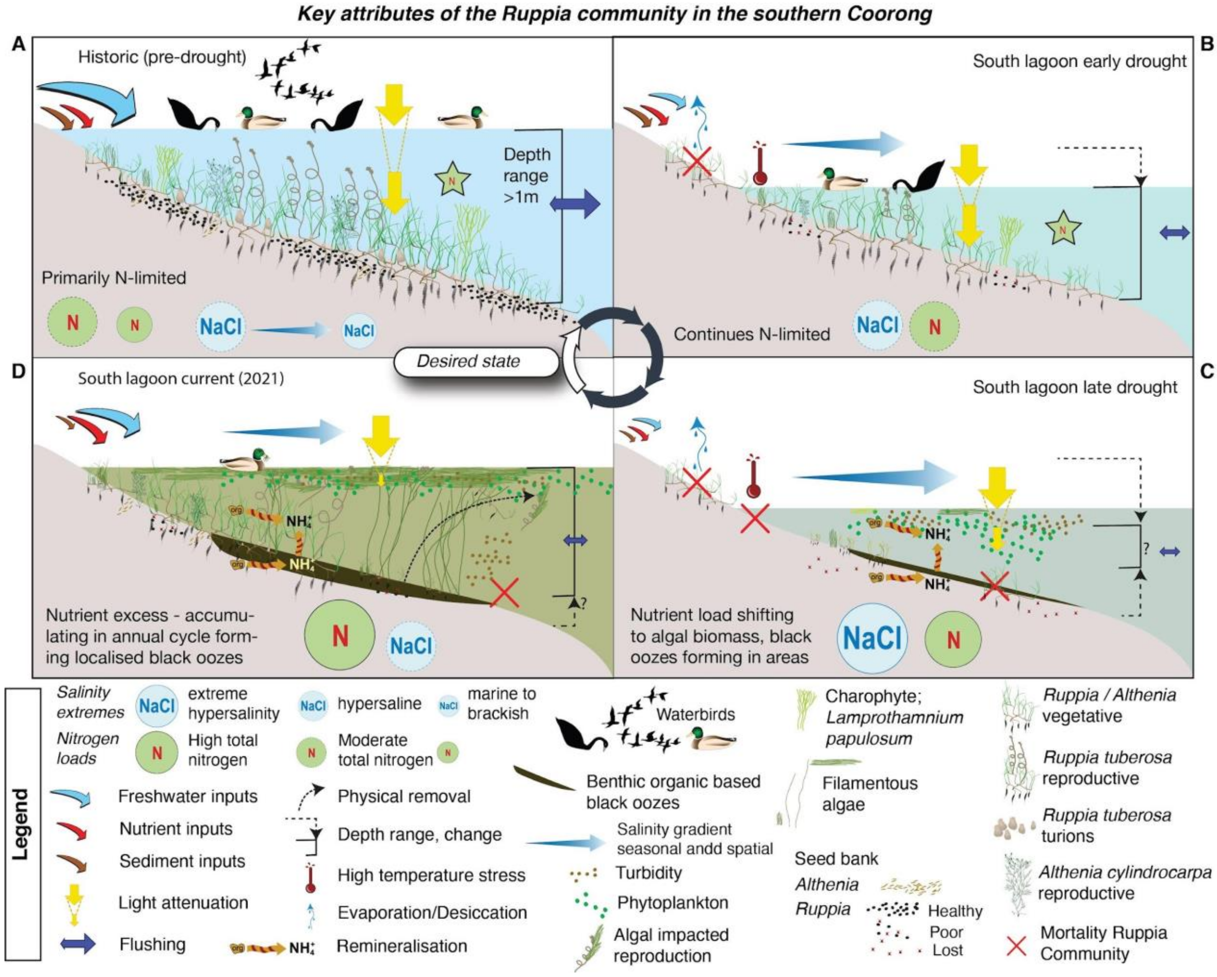

Figure 24. Summary diagrams reflecting the overall condition of the Ruppia Community in the southern Coorong across four time periods and its responses to the environmental pressures experienced; A. prior to the Millennium Drought (late 1990s), B. in the early stages of the drought with lower water levels and increasing salinity, C. late in the drought (~2009), effective loss of seed banks, extreme hypersalinity, D. the current state, hyper-eutrophic conditions occur across large sections of the southern Coorong and are causing filamentous algal and microalgal blooms leading to high organic loads and smothering sediments in organic sludge.

The changes experienced by the Coorong Ruppia Community due to extreme pressures of water availability and increasing salinities during the Millennium Drought were unable to be remediated by the return of water levels on their own. Re-establishing the dominance of aquatic macrophytes over algae is critical to achieving the outcomes for the Coorong as a whole.

4.3 The conservation, protection and issues of scale

4.3.1 The Ruppia Community components

The main features of the Ruppia Community are described in section 1.3 (The 'Ruppia Community' in the Coorong). The aquatic macrophyte species that make up this community are tolerant of a highly variable environment and, there are several features of these adaptations that are fundamental to considering restoration actions. The species share an ability to persist over an annual cycle that exposes them to variable water levels (lowest in summer, highest in winter) and are able to tolerate a wide range of salinities (i.e. Figure 3) within each annual cycle and across years. The life cycles of the aquatic macrophytes that are adaptable to extremely variable environmental conditions can be complex, epitomised by *R. tuberosa* (Figure 5), the dominant species in the southern Coorong under current conditions (Lewis et al. 2022).

A functional classification of seagrasses (marine submerged aquatic macrophytes) has been developed to improve management of these plants to different drivers of change and environmental pressures (Kilminster et al. 2015). Applied to the aquatic macrophyte species that occur in the Coorong, this functional classification identifies them as colonising species that have the ability to produce dormant seeds, have low physiological resistance to environmental pressures but have the potential for a rapid recovery from disturbance (Kilminster et al. 2015). In the Coorong, these species are able to thrive because of their ability to reproduce on an annual cycle under extreme conditions and develop propagules that persist across annual cycles on two different scenarios, a single season (i.e. the formation of turions) or multiple seasons (i.e. the formation of dormant seeds). The formation of propagules must be seen as the most critical stage in forming adaptable and resilient populations of plants under these dynamic conditions. Threats that impede the ability of the Ruppia Community to reproduce require addressing to prevent further loss of the plants in the system.

4.3.2 Future scenarios where the Ruppia Community could be impacted

Future scenarios where the Ruppia Community of the southern Coorong may be impacted will occur at different spatial and temporal scales depending on the pressures the aquatic macrophyte community experience. A range of scenarios outlining different scales of intervention actions based on these lessons learned (Table 8) provides activities that may need to operate in tandem with different scales of intervention options.

There are five categories of impact considered in Table 8:

1. Acute perturbation
2. Cumulative impacts
3. Inter-annual climate cycle
4. Climate change
5. Management action change.

These impacts result from a variety of pressures acting at difference scales in the system from local, within population scale effects to continental scale changes, including climate change. The risks of not acting to protect or rehabilitate the Ruppia Community could include; further loss of resilience, loss of the Ruppia Community, or increased dominance of nuisance primary producers (phytoplankton and filamentous algae, Table 8E). An important facet of the Restoration Strategy will be an evaluation of the environmental conditions driving change in the Ruppia Community at different temporal and spatial scales with an adequate monitoring program.

Table 8. Evaluation of responses of the Ruppia Community*, and co-associated primary producer communities including filamentous algae, to a range of spatial and temporal causes of change that are observed or expected to occur in the Coorong (Department for Environment and Water 2021c). Established condition targets are defined in (Department for Environment and Water and Natural Resources 2017, Paton et al. 2017b) and summarised in Appendix A.

Impact on the system acting as cause of change	1. Acute perturbation	2. Cumulative impacts	3. Inter-annual climate cycle	4 Climate change	5. Management action change
Example in Coorong context	Pulse of poor quality water (e.g. upriver derived black-water)	Increasing water column and sediment nutrient concentrations	Drought (e.g. Millennium Drought, 2001–2010)	Sea-level rise (such as scenarios based on current projections e.g. IPCC (2022))	Changing availability of environmental water (e.g. reduction in water for the environment) to manage Coorong water levels and salinity
A. Type of impact expected to be observed in aquatic macrophyte component of the Coorong ecosystem specifically the Ruppia Community	Significant decline in the Ruppia Community in area affected by direct short-term impact	Significant decline in the Ruppia Community across wide region Significant algal blooms, phytoplankton and macroalgae e.g. *Cladophora*/*Enteromorpha*, Figure 25 Increase in poor sediment quality e.g. based on Rapid Assessment Protocol (RAP), (Hallett et al. 2019)	Significant decline in the Ruppia Community at lagoon scale	Change in distribution due to system scale conditions e.g. water levels higher and consequences associated with habitat availability due to increased depth, sediment movement leading to siltation or erosion	Significant decline in the Ruppia Community at regional scale Significant algal blooms, phytoplankton and macroalgae e.g. *Cladophora*/*Enteromorpha*
Evidence of impact:	Across the area of impact there is a measurable reduction in condition targets for the Ruppia Community principally measures of vigour (abundance) and resilience (seed bank), also when widespread may include extent of occupancy (EOO) and area of occupation (AOO)	Regional scale reduction in condition targets for the Ruppia Community including EOO, AOO and seed bank Increased biomass of macroalgae (e.g. >184 g m^{-2}; Lewis et al. 2022) and density of phytoplankton	Loss of Ruppia Community from significant proportion of previous range (e.g. > 50% loss) Loss of resilience of Ruppia Community (e.g. seed banks < 2,000 seeds m^{-2})	Regional scale reduction in condition targets for the Ruppia Community, in particular AOO due to changed conditions leading to reduction in plant performance (e.g. reduced biomass)	Regional scale reduction in condition targets for the Ruppia Community, including EOO, AOO and seed bank Increased biomass of macroalgae and density of phytoplankton
B. Scale	Area of impact extends beyond a single bay or occurs in a critical habitat area for a region	Regional scale where significant proportion of the southern Coorong is impacted	Whole of system e.g. multiple year reduction in water levels and increased salinity leading to net loss of habitat availability across system	Whole of connected system	Regionally connected system e.g. water levels able to be modified by water releases from barrages in the Coorong North Lagoon in particular

Impact on the system acting as cause of change	1. Acute perturbation	2. Cumulative impacts	3. Inter-annual climate cycle	4 Climate change	5. Management action change
C. Potential intervention option/s	Intervention for critical habitats to recover Ruppia Community e.g. translocation of seed laden sediments, or rehabilitation of local conditions e.g. nutrient load reduction	Remediation of impacts enabling return to improved habitat quality at regional scale e.g. nutrient load reduction or salinity reduction	Facilitate the return of environmental conditions that constitute good habitat quality (i.e. water levels, salinity, nutrient loads).	Evaluate modified conditions and identify key ecosystem components and functions that have declined, new strategies may be needed Consider translocation for recovery of a functional Ruppia Community if environmental conditions are within expected tolerances	Reinstate management actions Identify alternative management action (e.g. alternatives to water for the environment)
D. Potential limitation to intervention application	Remediation of impacts not able to be achieved (e.g. nutrient loads not able to be removed) leading to ongoing poor habitat quality	Remediation of impacts not able to be achieved (e.g. nutrient loads not able to be removed) leading to ongoing poor habitat quality and continuing decline	Ongoing during period of climate cycle (e.g. duration of drought) Recovery period following drought, return of moderate conditions (e.g. 10-year recovery time following Millennium Drought with limited intervention) Potential for changed state of ecosystem due to loss of ecological components and functions during perturbation	Uncertainty around options with adequate lead times to implement meaningful intervention options	Availability of management action resources e.g. water for the environment allocations
E. Risk of no intervention	No recovery of impacted area or minimal loss of critical habitat area	Continued decline, long-term loss of habitat, failure of system to support critical ecological functions	Slower recovery time expected	Change of ecosystem state and loss of critical ecological functions	Continued decline of system including long-term loss of habitat

*Notes on factors that influence the options for implementing Ecological Restoration in the Coorong to recover a healthy aquatic macrophyte community:

Scale of impacts descriptors (not mutually exclusive)

- Coorong (whole area including from the Goolwa Channel north of the Murray Mouth to the southern reaches past Tea Tree Crossing in higher water level years)
- Coorong North Lagoon (CNL; Murray Mouth to Parnka Point; for modelling purposes sometimes divided into three sections)
- Coorong South Lagoon (CSL; Parnka Point to Tea Tree Crossing; for modelling purposes sometimes divided into three sections)
- Southern Coorong (Long Point to Tea Tree Crossing)
- Central section of the Coorong (area between The Needles Island and Hack Point where there is a natural constriction limiting connectivity)
- Critical habitat areas, ‘bay’ scale, where populations are capable of persisting

- ‘Critical habitat area’ defined as an area where aquatic macrophyte populations provide a significant proportion of the regional seed bank (e.g. > 25%) for the region (e.g. Coorong South Lagoon) so are critical to long-term resilience of the region.

The current basis for defining these desired outcomes is defined in the Ramsar Management Plan (Department for Environment and Water 2021a) which is informed by the Ecological Character Description (ECD) of the Coorong and Lakes Alexandrina and Albert (Department for Environment and Water 2021b), including a *Ruppia tuberosa* specific report (Paton et al. 2015b), and the desired State of the Southern Coorong (Department for Environment and Water 2021c) developed for the Healthy Coorong, Healthy Basin program.

The objectives for the aquatic macrophyte community are described in the Condition Monitoring Plan (Department for Environment and Water and Natural Resources 2017). Regional scale reduction in condition targets for the Ruppia Community including extent of occupancy (EOO, > 50 km of monitoring region), area of occupation (AOO, 80% of sampling sites within EOO have a Ruppia Community) and resilience (seed bank). Local scale condition for a vigorous population including: shoot count > 2,000 m^{-2}, flowering > 50% area, seeds in > 50% samples. Long-term resilience including: > 2,000 seeds m^{-2} within 10 years of perturbation or > 10,000 seeds m^{-2} within 20 years of perturbation.

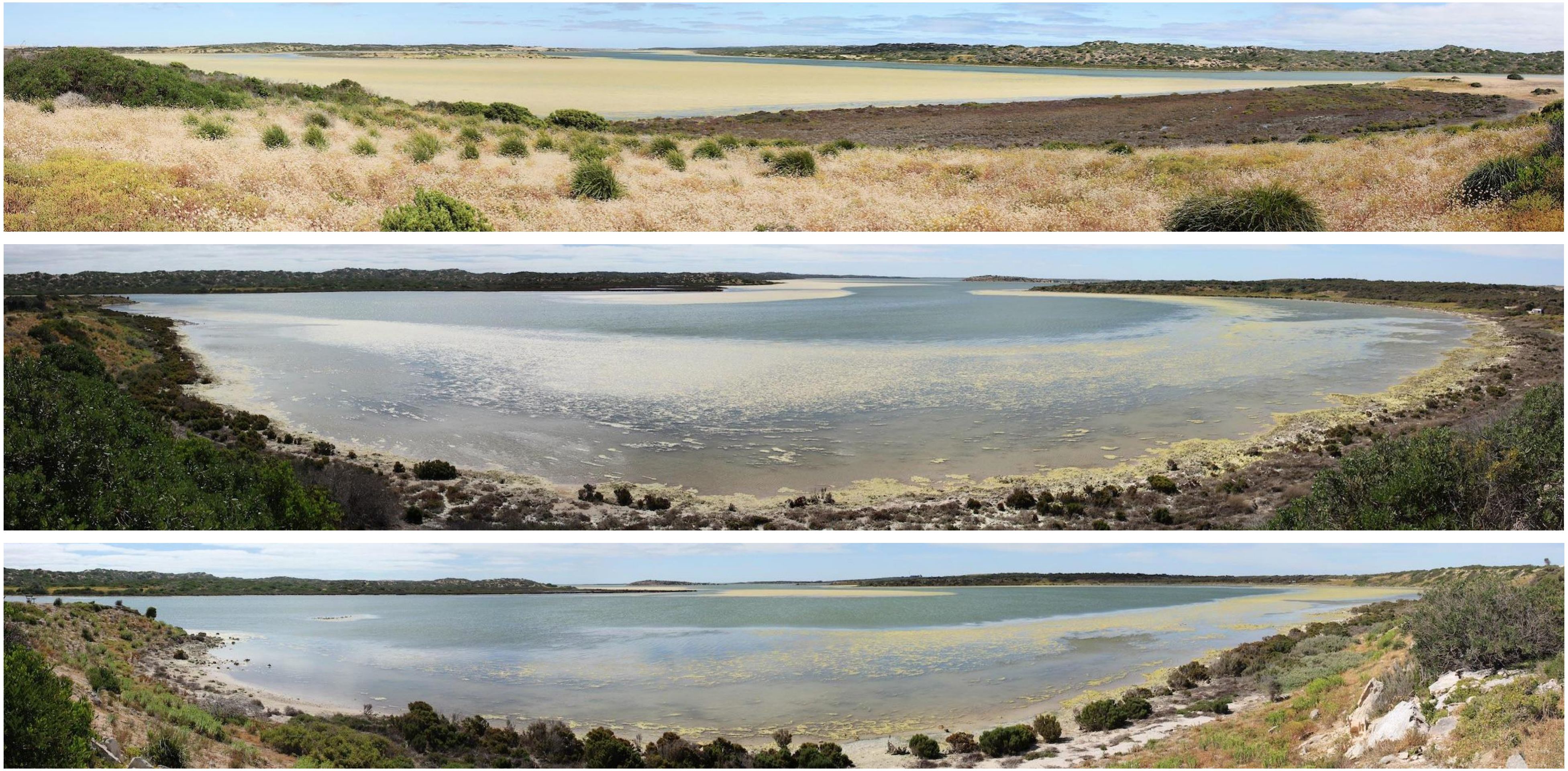

Figure 25. Filamentous algal mats seen as pale yellow/green areas across a large proportion of the area of the narrow channel at Parnka Point, that formed on the water's surface taken from the Parnka Point headland, 28 Nov 2016 (top) and 5 Dec 2016 (middle, bottom). Photographs by Ainsley Calladine, used with permission.

4.4 Workflow to implement the proposed southern Coorong Ruppia Community restoration cycle

The following workflow has been developed to scope the evidence base requirements for the next steps in undertaking potential restoration actions for the Ruppia Community in the southern Coorong. Visualised as a flow diagram (Figure 26) the numbered stages provide reference points that align with the overall restoration cycle (Figure 21). Each stage of the workflow has the context for its contribution to this objective summarised, and southern Coorong Ruppia Community examples provided with two alternates presented. The first stage is based on current Condition Monitoring Plan targets (Department for Environment and Water and Natural Resources 2017), the second, a proposed set of indicator types appropriate to supporting the broader restoration strategy.

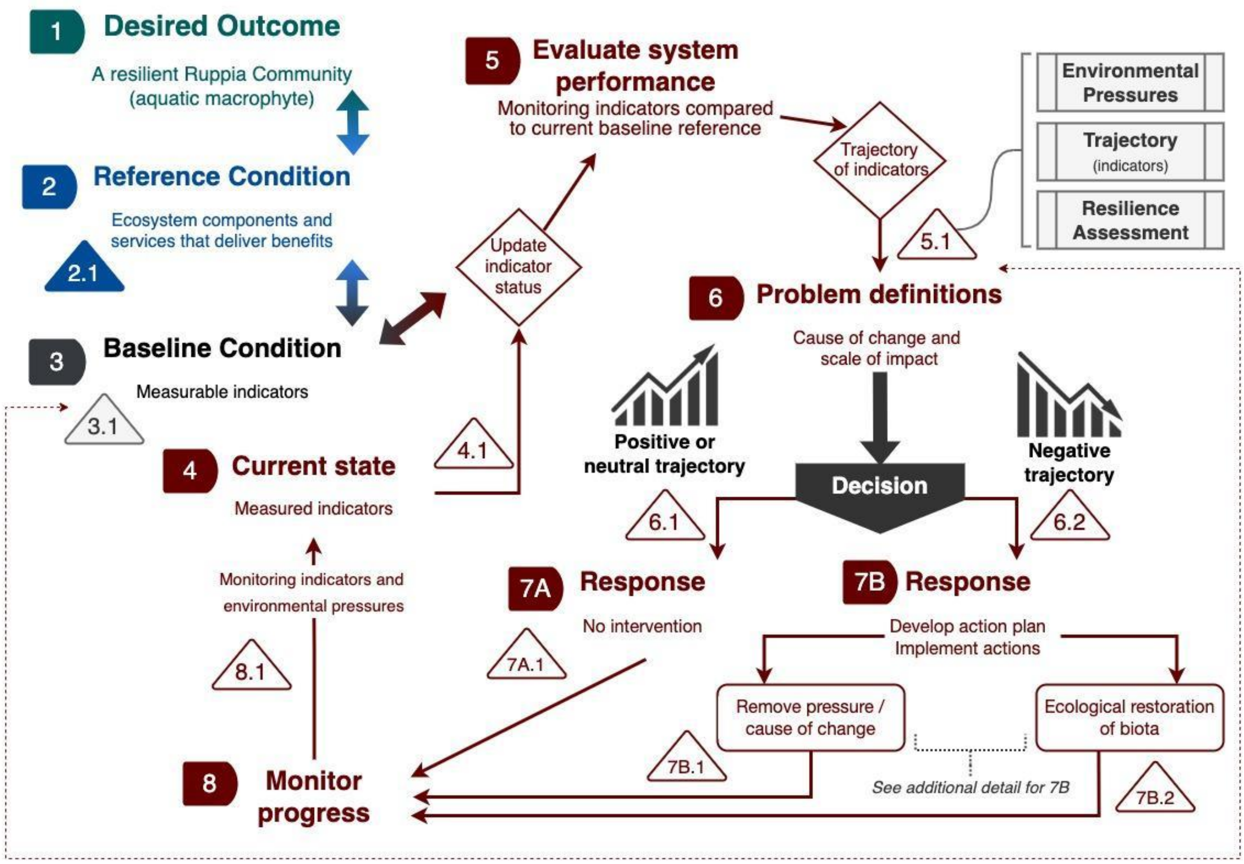

Figure 26. Restoration strategy workflow for the Ruppia Community in the Coorong. Numbers placed to provide reference to discussion points in the text or associated figures and tables. Additional detail is available for 7B in Figure 28.

4.4.1 Stage 1. Defining the desired outcome

In section 3.2 Ecological restoration principles and evaluating success, the desired outcome is described as:

> 'A resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions'

This is based on the long-term goals for the ecological state of the Ramsar site containing a healthy, resilient Ruppia Community, a keystone species in the Coorong ecosystem (Phillips and Muller 2006).

4.4.2 Stage 2. Establish the reference condition for the southern Coorong Ruppia Community

The reference condition is currently based Paton et al. (2015b), which was developed to inform the revision of the Coorong and Lakes Alexandrina and Albert Ramsar site ecological character description (ECD) (Department for Environment and Water 2021b). The preceding ECD published in 2006 (Phillips and Muller 2006) was comprehensive to the whole of the Ramsar site, including the Ruppia Community in the Coorong. The 2015 ECD is implemented in the most recent, updated Condition Monitoring Plan for the Living Murray – Lower Lakes, Coorong and Murray Mouth Icon Site (Department for Environment and Water and Natural Resources 2017, Paton et al. 2017b). The features of the current reference condition, and relevant policy or technical documents they are derived from, are summarised in Appendix A (Tables A1, A2, A3, A4) and the details of sources have been presented in section 3.2.

⇒ Restoration workflow assessment 2.1 (Figure 26); established reference condition targets and developed baseline condition targets to be reviewed with the availability of new data and updated trajectories. Also, to be reviewed if environmental conditions change or monitoring tools are modified.
   > Updated targets should be developed that utilise updated monitoring data from the ongoing The Living Murray initiative, outcomes from the Healthy Coorong, Healthy Basin Trials and Investigations projects and meet the criteria established in the updated Ramsar Management Plan (see section 3.2).
   > Summary of current targets;
      – Regional scale – *extent of occupancy* (EOO, > 50 km of monitoring region), *area of occupation* (AOO, 80% of sampling sites within EOO have a Ruppia Community) and *resilience* (seed bank)
      – Local scale – condition for a *vigorous population* including shoot count >2,000 m^{-2}, flowering >50% area, seeds in >50% samples.
      – Long-term resilience – *seed banks* of > 2,000 seeds m^{-2} within 10 years of perturbation or > 10,000 seeds m^{-2} within 20 years of perturbation.
      – These reference condition targets have been adopted for the resilience assessment and evaluation of trajectory for the restoration workflow.

4.4.3 Stage 3. Baseline condition to conduct evaluation of indicators

The baseline condition adopted would serve as the reference data set/s for comparing monitoring data to establish trajectories towards long-term goals. The evaluation presented in the *South Australian River Murray Basin Plan Environmental Outcome Evaluation: Coorong, Lower Lakes and Murray Mouth (CLLMM) Priority Environmental Asset* (Department for Environment and Water 2020b) presents a sound strategy for assessing trends using current data sets. However, monitoring restoration actions effectively will require the inclusion of new data types, and an evaluation framework that will provide clear reference points, such as achieving particular targets, e.g. 2000 seed m^{-2} for monitoring change over time. Current monitoring methodologies, derived during the period of extreme conditions at the end of the Millennium Drought, should be reviewed for relevance to and interpretation of current conditions.

⇒ Targets for future monitoring should be integrated across the range of spatial and temporal scales for the system. A recommended list of targets to evaluate progress towards the restoration goal of the Ruppia Community having '*widespread populations of high abundance relative to prevailing conditions*' has been developed (

⇒

⇒ Table 9). Among these are updates associated with currently known outcomes from the Healthy Coorong, Healthy Basin projects.

⇒ Restoration workflow assessment 3.1 (Figure 26); baseline condition targets for evaluation of current state derived from the analysis above following review.

⇒ Current targets follow Condition Monitoring Plan for The Living Murray initiative.

Table 9. Recommended table of indicators to evaluate progress of the Ruppia Community towards long-term objective: 'A resilient Ruppia Community with widespread populations of high abundance relative to prevailing conditions'.

Attribute	Indicator Note may have components within each	Proposed measure Note will need to define scale	Baseline data available? Note refinement for application may be needed	Reference
Physical conditions				
	Sediment type	Rapid Assessment Protocol (RAP) 'good' i.e. positively correlated attributes	Yes, 2021 Reproductive survey and Sediment survey	Lewis et al. (2022) Huang et al. (2022)
	Hydrology (flow, depth range)	Water levels	Yes, ongoing monitoring	Healthy Coorong Healthy Basin (2022a)
		Flow across system including residence time for sections	Yes, model based on data available from long-term monitoring stations	Healthy Coorong Healthy Basin (2022a)
	Salinity and nutrient concentrations	Salinity concentrations	Yes, ongoing monitoring data available from long-term monitoring stations	Healthy Coorong Healthy Basin (2022a)
		Nutrient concentrations	Yes, water column from ongoing water quality monitoring program, sediment concentration from T&I Component 1 and 2	Healthy Coorong Healthy Basin (2022a) Mosley et al. (2020), Huang et al. (2022), Priestley et al. (2022) Waycott et al. (2022)
Primary producer community				
	Ruppia Community	Multiple species of aquatic macrophytes present across sites the system and community composition	Yes, different methodologies from HCHB and TLM	Lewis et al. (2022) Paton et al. (2017b, 2021)
	Filamentous algae (only localised and small patches <10 m²)	Biomass and cover	Yes, preliminary HCHB	Lewis et al. (2022)
	Microalgae (community types and concentrations do not inhibit light to <20% incident light	Water column concentrations declining, healthy (not harmful) microbial community associated with Ruppia Community	Yes, Water Quality Monitoring Program and HCHB	Healthy Coorong Healthy Basin (2022a) Jamieson et al. (2022)
Plant community distribution				
	Extent Ruppia Community	Presence across extent of region	Yes, different methodologies from HCHB and TLM to be aligned	Lewis et al. (2022) Paton et al. (2017b, 2021)
		Condition of the populations, shoot counts or biomass across proportion of samples at sites	Yes, different methodologies from HCHB and TLM to be aligned	Lewis et al. (2022) Paton et al. (2017b, 2021)
	Seasonal presence	Expected seasonal presence; germination, vegetative growth, flowering, seed set, seed bank	Yes, different methodologies from HCHB and TLM to be aligned	Lewis et al. (2022) Paton et al. (2017b, 2021) Kim (2014)
	Ruppia Community resilience	Flowering frequency, seed set, seed bank production (medium term) Turion production (short term)	Yes, different methodologies from HCHB and TLM to be aligned	This report Waycott et al. (2022) Paton et al. (2015b), Paton et al. (2017b) Lewis et al. (2022)

Attribute	Indicator Note may have components within each	Proposed measure Note will need to define scale	Baseline data available? Note refinement for application may be needed	Reference
Ecosystem function				
	Habitat provision	Shelter for juvenile fish from predation, structure for invertebrates to settle, stablised sediments	Some available, but need evaluation for objective based monitoring	Collier et al. (2017) Paton et al. (2015b), Paton et al. (2017b)
	Biomass production	Longer term carbon and other nutrient storage, food web resources	Some available, but need evaluation for objective based monitoring	Lewis et al. (2022) (Delroy 1974)
	Sediment and nutrient cycling	Ecological engineering oxygenation of sediments around roots, nutrients enter organic pathways via longer lived tissues	Some available, but need evaluation for objective based monitoring	Mosley et al. (2020), Huang et al. (2022), Priestley et al. (2022) Waycott et al. (2022)
External exchanges				
	Landscape connectivity	Water connectivity between South East flows, River Murray and Coorong Connectivity across Coorong Lagoons Residence times	Yes, model based on data available from long-term monitoring stations	Healthy Coorong Healthy Basin (2022a)
	Genetic diversity and connectivity	Avoid small population size Encourage gene flow across populations and regions	Yes, some basic data, needs review	Waycott et al. (2022) Lewis et al. (2022)
	Habitat links	Detrital pathways and microbiome	Yes, some basic data microbiome, detrital pathways poorly known	Jamieson et al. (2022)
Threats (absence)				
	Physical disturbance	Observation of impacts that will physically disturb plants, vehicles (cars, boats), digging or dredging, changed water movement direction and energy	No	
	Invasive species	Species of plants, algae or animals that modify the system	No	
	Pollution and nutrient pulses	Presence of toxic chemicals	No Some point data from state wide pesticide (EPA) and heavy metal historical records	e.g. Jenkins (2013) Grattan et al. (2004)
		High levels of nutrients in pulses	Yes, water quality monitoring data	Mosley and Hipsey (2019)

4.4.4 Stage 4. Description of the current state of the Ruppia Community based on measured indicators

⇒ An indicator suite summarised in

⇒ Table 9 would provide a strategic monitoring program for evaluating the current state of the southern Coorong with the focus on the Ruppia Community. Environmental parameters collected at an appropriate spatial scale would be highly informative. For example sediment quality, based on a straight forward rapid assessment protocol (RAP, Hallett et al. 2019), can provide evidence of habitat quality for the Ruppia community. Poor sediment quality, as evaluated using the RAP, was correlated to poor plant performance (lower biomass) in recent southern Coorong wide surveys (Lewis et al. 2022). Ongoing hydrological monitoring stations and a water quality monitoring program also provide important evidence of water levels and other basic water descriptors such as salinity and temperature.

At present, indicators of Ruppia Community condition are collected following the monitoring for The Living Murray initiative (Murray–Darling Basin Authority 2022). Other data sets are collected separately as a part of long-term watering plan monitoring and other programs. The use this data as a co-ordinated evaluation process is achieved post-hoc and analysis done similarly.

⇒ Restoration workflow assessment 4.1 (Figure 26); the goal is a set of indicators compiled for comparison with baseline against targets with known relationships and expected trends e.g. Table 10.

⇒ Table 10. Potential indicators for a Ruppia Community monitoring program that would inform decision making as to the needs for intervention, derived from

Table 10. Potential indicators for a Ruppia Community monitoring program that would inform decision making as to the needs for intervention, derived from.

ENVIRONMENTAL PRESSURES	INDICATOR TRENDS POSITIVE	INDICATOR TRENDS NEGATIVE	RESILIENCE LONG-TERM
Sediment type	Ruppia Community composition	Filamentous algae (low – cover, biomass, condition)	Ruppia Community resilience (e.g. decision tree approach)
Hydrology, flow	Ruppia Community extent (over defined area)	Microalgae (low concentrations)	Genetic diversity
Hydrology, depth range	Ruppia Community condition – vegetative (density i.e. biomass or shoot count)	Invasive species (absent)	Genetic connectivity
Salinity concentrations	Ruppia Community condition – reproduction (flowering, seed set, seed bank, turion production)	Harmful species (absent/not harmful)	
Nutrient concentrations	Biomass production (sequestration)	Nutrient pulses (small scale and rare)	
Sediment and nutrient cycling	Seasonal presence (lifecycle critical times)	Pollution (below advisory levels/absent)	
Physical disturbance	Ruppia microbiome healthy	Ruppia microbiome harmful	
Landscape connectivity	Habitat provision (Ruppia for others)		
	Habitat links (water connectivity)		

4.4.3 Stage 5. Evaluation of current state compared to the baseline condition establishing the trajectory towards targets including an assessment of Ruppia Community resilience

Evaluating the trends towards a resilient Ruppia Community, should include a minimum of three types of indicator and assessment and provide the evidence base to be used for decision making.

⇒ Restoration workflow assessment 5.1 (Figure 26); a set of indicators compiled and prepared for comparison with baseline against targets with known relationships and expected trends.

The indicators proposed (Table 10) for updated monitoring of the Ruppia Community would conform to a decision tree approach as a part of the next steps and include indicators on the environmental pressures, indicators of biological status and threat status, and long-term resilience (i.e. Figure 27).

Resilience assessment decision tree

A resilience metric has been developed for the dynamic community of seagrasses in the monitoring of habitat quality in the Great Barrier Reef Marine Monitoring Program (GBR MMP) (Collier et al. 2021). Adopting a similar approach, we can utilise data already being collected to evaluate resilience empirically and use as a monitoring tool. The resilience metric developed for the GBR MMP utilised a 15–20 year data set and known local conditions to assess meadow scale loss and gain through their routine monitoring (Collier et al. 2021). Central to the use of this approach was a detailed knowledge of the community composition, intra- and inter-annual variation in the reproductive effort and population composition of the multi-species communities being monitored. This approach has been adapted to generate a resilience assessment, initially semi-quantitative, but as data sets become available would be more quantitative (Figure 27). This approach has been developed to recognise where offsets in current shorter term condition can still lead to moderate long-term resilience, and a positive trajectory (Figure 27). Further, this approach has potential application in the modelling undertaken to determine habitat suitability for the Ruppia Community in the southern Coorong as a component of the Coorong Dynamics Model developed for supporting decision making in the system (Collier et al. 2017, Hipsey et al. 2020, Hipsey et al. 2022).

Feedback to the baseline condition

At this stage of the workflow, there is an opportunity to re-evaluate baseline conditions and to adapt the program depending on the trajectory. Several causes would lead to the requirement for adaptation including;

- emergence of new pressures on the Ruppia community creating risk for achieving restoration outcomes,
- achieving an interim target that established a next stage of restoration.

For example, recognition of the increasingly persistent hypersalinity and hyper-eutrophic conditions experienced across the southern Coorong since 2010 (Mosley et al. 2020) has led to actions being developed to reduce nutrient loads across the system. The outcome for the health of the Ruppia Community will be to reduce the prevalence of algal blooms including filamentous algae that interfere with reproduction preventing seed set in the Ruppia Community. In addition, waterbird foraging and shorebird feeding opportunities will improve. The baseline conditions being established through outcomes of the Healthy Coorong, Healthy Basin Trials and Investigations scientific investigations will inform new baseline conditions and reference condition targets associated with nutrient loads and interactions of nutrients with sediments and plants. In addition, these features are being incorporated into the Coorong Dynamics Model (below).

The Ruppia Habitat Suitability Index, the Ruppia HSI

The development of decision support tools for the ongoing management of the Ramsar site, and more recently the Coorong, has included a specific Ruppia HSI (Ruppia Habitat Suitability Index) to estimate habitat suitability for the Ruppia Community in the southern Coorong (Collier et al. 2017, Hipsey et al. 2020, Hipsey et al. 2022). The Ruppia HSI has been compiled as a part of the Coorong Dynamics Model suite of tools being used for estimating outcomes posed for the state of the Coorong and is currently being updated based on the findings of Lewis et al. (2022) (Hipsey et al. 2022). The Coorong Dynamics Model has been developed as a tool to quantify nutrient cycling and habitat changes within the Coorong ecosystem in response to different environmental conditions and is used to assess management scenarios supporting decision-making. The highly informative outputs from this modelling suite provide an integrated methodology for evaluating current and potential future states based on monitoring data. Incorporation of the Ruppia HSI would be one of the next steps in a pipeline for the interpretation of the Ruppia Community monitoring.

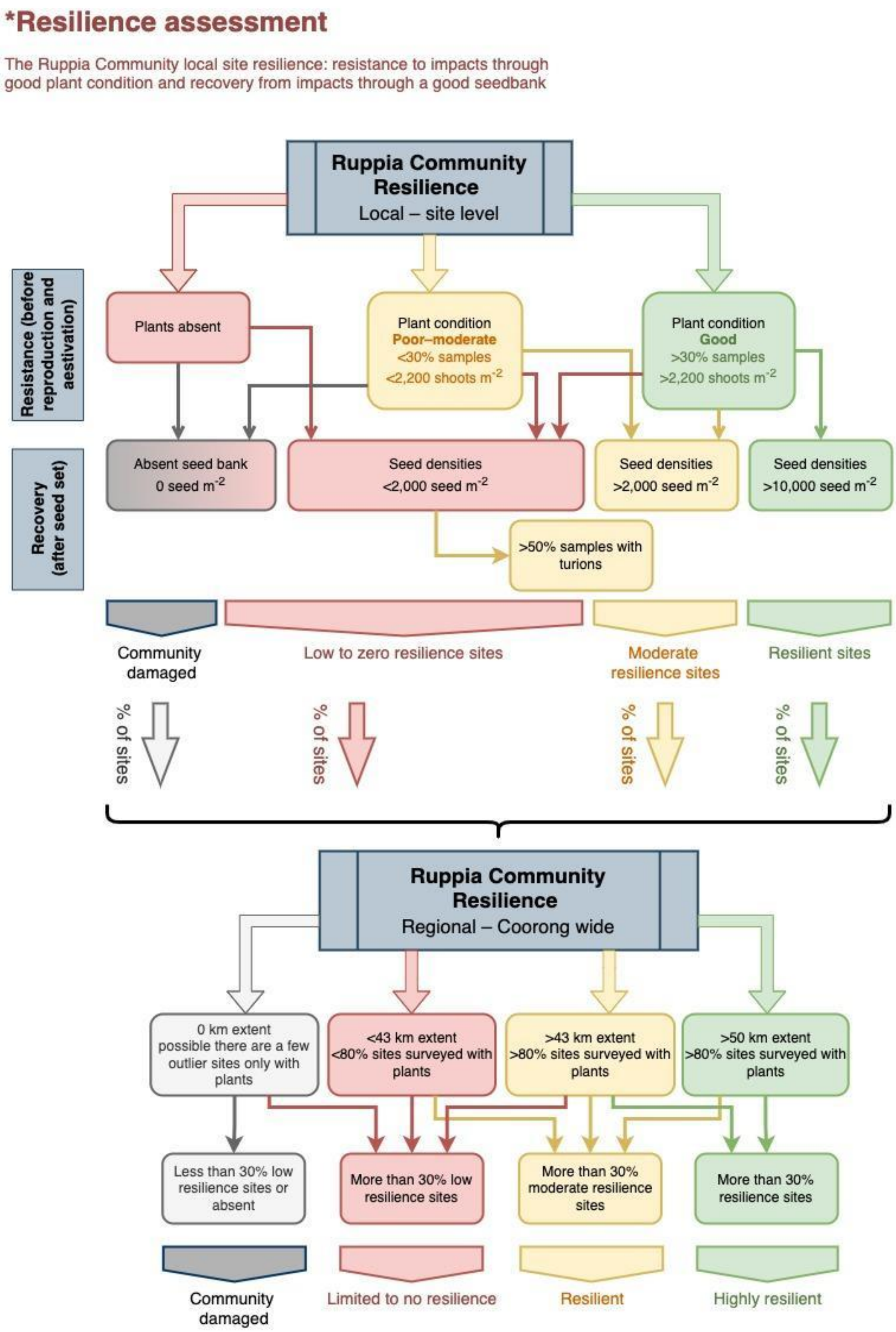

Figure 27. Framework for the assessment of resilience in the Ruppia Community in the Coorong with targets currently in use for condition monitoring (Department for Environment and Water and Natural Resources 2017, Paton et al. 2017b).

4.4.4 Stage 6. Evaluation outcomes and the problem definition for developing actions

Outcomes from the stage 5 evaluation process inform estimations of system performance and are fundamental to identifying next steps to improving the system. At this stage, the nature and scale of any problems should be identifiable from the monitoring data and the evaluation process. In addition, outcomes should be informed by an external consultation process such as technical review of data and interpretation and non-scientific and community consultation to establish if results are in alignment with observations and expectations.

Interpretation of monitoring results for many ecosystems involves comparative analysis with a reference system. However, for the Ruppia Community the lack of an indigenous reference system, means it is necessary to use pre-defined conditions as a metric to measure progress towards expected outcomes. For example, a target based on current knowledge, such as a seed bank target of > 2,000 seed m^{-2} as the long-term metric of resilience for a healthy Ruppia Community, would indicate the system was trending towards long-term resilience although not in time to meet a 2019 target.

If key thresholds are exceeded, or equivalent for project specific restoration targets, the options to consider would each lead to alternative action plans being developed.

- ⇒ Restoration workflow assessment 6.1 (Figure 26); the evaluation identified that there is insufficient evidence for the need to intervene or that the system is progressing as expected along the planned trajectory. The action plan to be developed would highlight any modifications or concerns for assessment in the next round of the monitoring cycle.
- ⇒ Restoration workflow assessment 6.2 (Figure 26); the outcome of evaluation indicates a strategy to mitigate the pressures on the system is required or intervention in the rehabilitation of biota is required.

Fundamentally, the decision to intervene should reflect whether the survival of the Ruppia Community and/or the trajectory of recovery, would only occur if the ecological functions are reinstated. The long-term goal is to establish a viable (self-sustaining), resilient Ruppia Community where its persistence will reduce the likelihood of its loss following future impacts.

4.4.5 Stage 7. Intervention options, decisions and action plans

Alternative options would need to be considered once the trajectory of the system is identified. Any alternative options should incorporate consideration of the scale and nature of the impact which led to the current state and, its relationship with the long-term goals. Different types of impact would each lead to alternative action plans being developed.

- ⇒ Restoration workflow assessment 7A (Figure 26); pathway where in 6.1 no trigger for intervention was identified and the action would be that the monitoring cycle continues.
- ⇒ Restoration workflow assessment 7B (Figure 28); if 6.2 trigger/s for intervention were identified there are two higher level options:
  - o 7B.1: it is determined that threats to the Ruppia Community are unable to be managed without additional intervention. The scale of intervention may be large (e.g. examples summarised in Table 8) and involve physical, chemical or hydrological modification of the system.
  - o 7B.2: it is determined that ecological restoration of the biota is required. The assumptions involved (Figure 28) include the availability of adequate biological and ecological knowledge to plan restoration actions, that restoration sites will have had threats remediated, there are donor sites or sources of propagules to undertake restoration, and that the restoration actions won't cause irreparable harm to donor sites.
- ⇒ Once the nature of the restoration action required is established, the action plan can be developed, including cross referencing with the established monitoring plan to align outcomes with indicator and other data being collected and analysed.

Once the nature of the intervention strategy has been developed there are numerous sources of information available to support the development of an action plan. These include; technical feasibility assessment for the 2012–2014 translocation actions (chapter 0); research on *R. tuberosa* growing options and the pilot study which was conducted prior to implementation (Paton and Bailey 2010); project implementation (Department of Environment Water and Natural Resources 2014b); reviews of the biology and ecology of the Ruppia Community (list of resources at the end of section 1.3); and broader translocation and ecological restoration resources (Paling et al. 2009, Katwijk et al. 2016, Commander et al. 2018b, Tan et al. 2020, SERA 2021b).

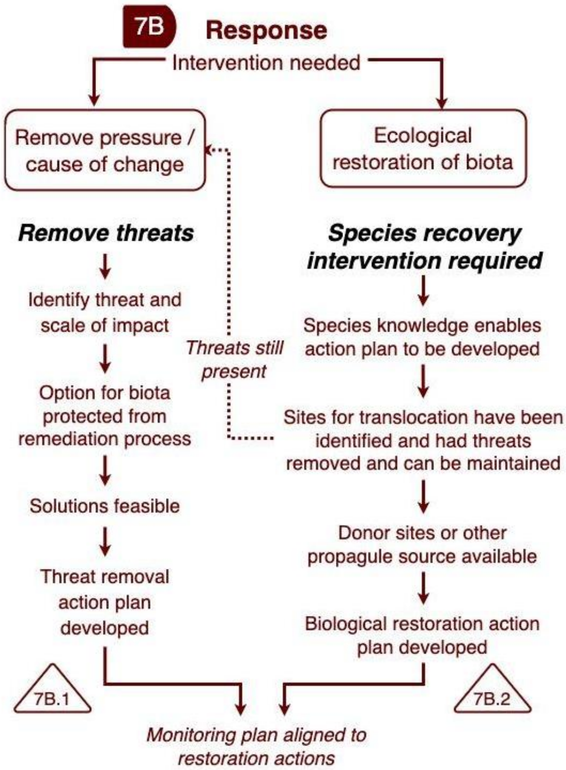

Figure 28. Restoration strategy workflow details for 7B (refer to Figure 26 for other workflow components). This section provides critical elements to decision making for moving to develop a restoration plan for different strategies and scales of restoration intervention.

4.4.6 Stage 8. Implement action plans and monitor progress feed into adaptive cycle to achieve outcomes

Implementing the action plans and monitoring the system throughout the process of undertaking restoration actions is where the workflow becomes operational. The documentation and decision making that underpins the actions being implemented will provide critical reference resources for the work to be done. It is crucial that the documentation, data and evidence base is available to the teams undertaking the work and that appropriate project governance supports actions, particularly where they involve multiple simultaneous actions. In the implementation process it is important to set objectives that make clear what needs to happen for the actions to achieve the goal for the plan. Detailed objectives allow the tracking of progress towards the translocation becoming a self-sustaining Ruppia Community where there is evidence of its resilience.

The monitoring and evaluation of progress to inform the next steps is equally important as the restoration actions themselves. Delivery of outcomes will typically take multiple cycles to achieve, sometimes over many years depending on the scale and nature of the actions, and a number of monitoring options have been proposed in this workflow that would support evaluation of implementation and progress. A well-established approach to interpreting progress includes the SERA progress assessment template (SERA 2021b) which has been adapted here for use in the southern Coorong Ruppia Community Restoration Strategy.

⇒ Restoration workflow assessment B (Figure 26); monitoring of biological and physical environment indicators, environmental pressures and restoration action focussed attributes to inform the next cycle of the Current State (stage 4).

⇒ The progress assessment template for assessing the state of the Ruppia Community in the Coorong (Figure 29) is a '5 star' rating process. The indicators for the program (

⇒ Table 9) are rated against progress towards to the overall restoration goal – establishing the Ruppia Community which is viable (self-sustaining) and resilient without further intervention. This highest rating suggests the persistence of the Ruppia community will have high likelihood following future impacts. Scores were qualitatively assessed as follows:

1. Limited progress, but that actions are to be implemented e.g. strategy for reducing nutrients and maintaining water levels developed and implementation planned.
2. Actions are being implemented on pathway to ecological resilience for the Ruppia Community e.g. water levels being maintained with management levers to enable completion of life cycle each year.
3. Community on trajectory to meet long term targets and new ecological functions becoming evident, e.g. local population vigour improved to be healthy and evidence of sediment quality improvements due to oxygenation observed at sites where population density targets met.
4. Positive trajectory well established, additional ecological functions supported, evidence of resilience in some attributes well established e.g. widespread Ruppia Community, maintained and increasing community diversity.
5. Ruppia Community has reached its overall goal applied to each attribute.

*note that if no progress or planning made not scored (i.e. remains blank).

The assessment format in Figure 29 is amenable to a rapid assessment process and visualisation for communication and reporting of the program. However, typically detailed information would sit behind these assessments and be supported by data sets including baseline data and expected outcomes for achieving the goals.

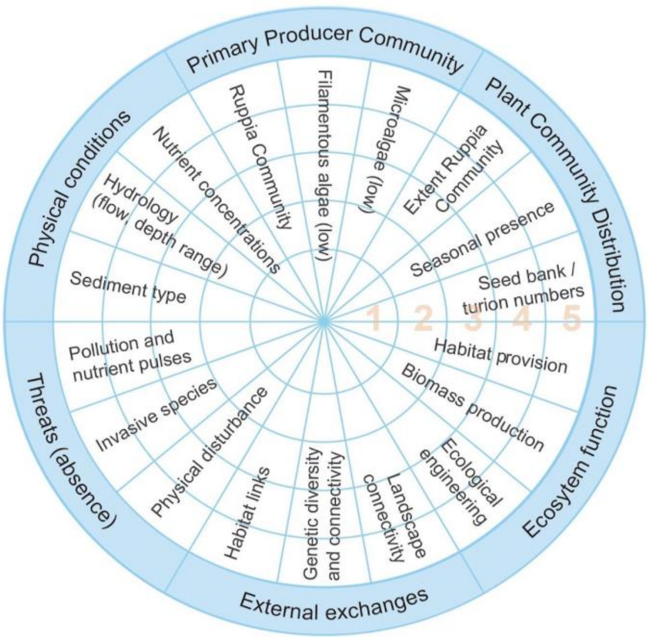

Figure 29. Progress assessment template adapted for assessing the state of the Coorong Ruppia Community with goals supported by monitoring activities and restoration actions informing the progress towards targets (SERA 2021b). The scale should correspond to progress towards recovery outcomes that have been established for the program of work.

The application of this progress assessment has been completed based on the lessons learned summaries (Table 7) and applying expert opinion to assigning ratings. This process of generating the ratings for visualisation of the relative performance of each indicator type raised the following points for consideration in adopting this or a similar approach to reporting or summarised reporting:

- A method for combining data sets should be developed to ensure consistent rating of multiple indicators, particularly the biological indicators such as those grouped under 'Ruppia extent' which is a combination of extent, condition and aspects of phenology such as flowering and turion production.
- A set of critical disturbance factors that directly impact the Ruppia Community is needed. In this assessment, expert opinion was based on consideration of disturbances that impact broad life history and general plant survival.
- There are knowledge gaps associated with habitat links, genetic connectivity, landscape connectivity, pollution, and invasive or harmful species. Some available data sets may be beneficial for Ruppia Community evaluation, however they are not collected in this context, nor has there been direct consideration for using them for the purpose of monitoring. Given the impact these factors may have on the ability of the Ruppia Community to be restored, an assessment of the nature and scale of indicators for these factors should be considered.
- If a five level ranking is adopted, establishing a documented, enumerated rating system would be the next step.

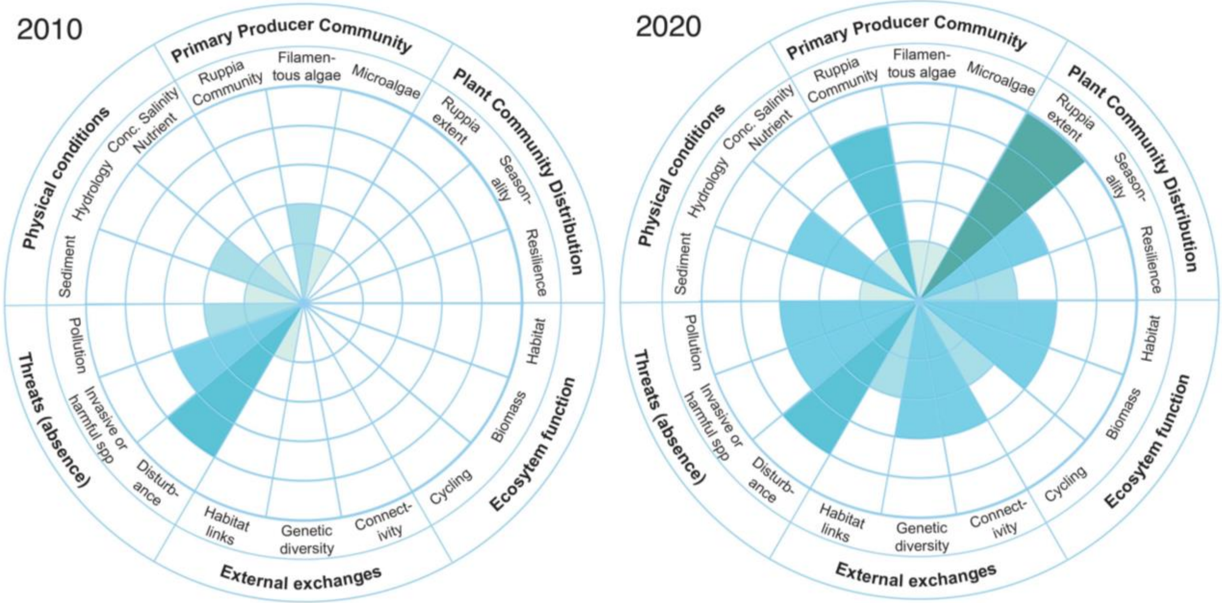

Figure 30. Progress assessment evaluation for the two examples of restoration actions, 2021 and 2020, to support restoration of the Ruppia Community in the Coorong (Table 7).

The outcome of this assessment clearly shows the shifts in the Ruppia Community over the last decade (Figure 30). Environmental pressures (see Table 10 for indicator categories) have changed very little with respect to their conditions for Ruppia community growth, although water levels and availability have improved, primarily due to wetter years. Climatic conditions, such as recent La Niña weather patterns, have affected the region and Ruppia Community growth (Lewis et al. 2022). Compared to 2010 the Ruppia Community measures have improved, principally the presence, extent, and condition of plants and populations, but also the services they provide. Resilience remains relatively poor. At the site level there are locations that meet the 2019 target for >2,000 seeds m^{-2}, however this was not observed across the surveyed area of the southern Coorong in 2021 (Lewis et al. 2022). These ratings provide clear starting points, for the work underway in the Healthy Coorong, Healthy Basin program to consider for improving the health of the Ruppia Community and Coorong overall.

4.5 Other considerations in achieving restoration outcomes

Ecological restoration of the Ruppia Community is limited by the extreme nature of the southern Coorong, as well as the extreme adaptations the aquatic macrophytes that occupy it have to survive there. This proposed Restoration Strategy provides an approach that should allow identification of options for the implementation of actions as the system changes. When intervention is determined to be needed, the actions possible will be determined by the scale of the recovery needed. In the case of the Coorong in 2010, translocation of seed laden sediments was successful and provide an example of relatively simple methods applicable over larger areas. Unfortunately, the lack of an ongoing monitoring program limits the interpretation of how these translocations affected sites other than the immediate translocation area.

In 2021, the Ruppia Community of the southern Coorong was exposed for an extended period to hyper-eutrophic conditions and experienced a wide salinity range up to 140 g L^{-1} in 2021-22 monitored sites. The Ruppia Community is found across what are likely to be the majority of locations where it is able to inhabit, however, plant condition is impacted by poor water quality and poor sediment quality. The impacts of this poor sediment quality on seed germinability and seed bank longevity remain to be tested. The 2021-22 reproductive season had a strong shift to turion formation and seed banks in December 2021 were poor in most areas. Given the long-term recovery processes that may be required for the system to progress to a resilient state the need for better linkages between environmental variability and population growth is important.

4.5.1 Recovery timelines for 'annual' aquatic plant species and the importance of seed banks

The trajectory of the Ruppia Community component of the Coorong ecosystem continues to be positive since the end of the Millennium Drought. Consideration of the factors associated with population recovery timelines for the Ruppia Community in the southern Coorong environment could be confusing. The relative success of short lived plant species to recover from major disturbances often relies on a substantive seed bank or high dispersibility and is typically classified as r-selected following the classic model (Grime 1974). Establishing survival success of restored populations of plant species has been observed to vary considerably and is affected by species life history traits, particularly individual turnover rates (Bialic-Murphy et al. 2022). As a community comprised of colonising species, the Ruppia Community relies heavily on an annual turnover of seeds, and a persistent seed bank.

The dispersal of seeds along the spatial extent of the Coorong is important, and it is likely that in the earlier stages of recovery (e.g. Figure 3C), seed production would be slow to reach numbers where dispersal to other populations could be achieved. This would be exacerbated by the physical nature of the southern Coorong waterway and the levels of connectivity between the North and South Lagoons. Seed dispersal would be limited by the exchange of sediments and water for in situ physical movement lengthwise along the system. In addition plant foraging waterbirds associated with the Ruppia Community have declined, reducing bird related seed dispersal (Paton et al. 2018b, Murray–Darling Basin Authority 2022), although this seed dispersal remains unstudied. It is likely that the early stages of recovery were dispersal limited (Kendrick et al. 2012) and now that seed banks are widespread (Paton et al. 2021, Lewis et al. 2022) responsiveness to short-term perturbations will improve.

4.5.2 Genetic diversity and genetic connectivity

Genetic diversity of species and populations of species is important to consider when undertaking restoration of native plants (Commander et al. 2018a). Genetic diversity is crucial as it is the basis for maintenance of fitness, and facilitates evolution and adaptation of species and populations (Commander et al. 2018a). One of the most significant long-term consequences for the loss of genetic diversity can be a reduction in adaptive potential (Menges 2008, Commander et al. 2018b, SERA 2021b). This is of particular relevance to restoration actions where restoring the potential for survival is a primary goal (Menges 2008, Commander et al. 2018b, SERA 2021b). In addition, the genetic make-up of species and their populations can affect restoration outcomes. For example, within-species variation in ploidy level (some diploid, some polyploid) makes possible hybridisation when different ploidy levels are translocated together leading to poor outcomes for the viability of offspring, as occurred in the Button Wrinklewort (*Rutidosis leptorrhynchoides*) (Weeks et al. 2011).

The inclusion of genetic diversity assessments is often overlooked for species that are not rare or isolated populations of species with widespread distributions. Where loss of a species from a region or location or where a significant decline in population size has occurred, the potential loss of genetic diversity can lead to inbreeding (Coates et al. 2018). A high priority should be to establish the scale of potential for inbreeding including the genetic diversity of donor sites if translocation is being considered. If inbreeding likely, planning for genetic resilience should be included in the restoration strategy. In addition, choice of source material (provenance of propagules) used in translocation actions will need to recognise that under long-term change in local climate conditions additional adaptive capacity may be needed to enhance outcomes (Weeks et al. 2011, Prober et al. 2015, Coleman et al. 2020, SERA 2021a). The adoption of climate-adjusted provenancing for the Ruppia Community in the southern Coorong is compelling given the already extreme conditions that the aquatic macrophytes of the region are exposed to. More detailed identification of source material and evaluation of the conditions that are likely to be needed in the future will be required and represents a significant knowledge gap. Unfortunately, few studies are available on the population genetic diversity of any *Ruppia* species (Triest et al. 2018, Beirinckx et al. 2020, Triest et al. 2021) and none on *Althenia* species from around the world. The result is that there is a lack of comparative evidence from other ecosystems to inform strategies. Given the detection of cryptic diversity in the surveys associated with this program broader genetic studies to inform restoration actions would be of considerable value (Lewis et al. 2022).

The restoration of the Ruppia Community in the Coorong also includes multiple species as reported by Lewis et al. (2022) and confirmed by the presence of visibly different seeds in the seed bank, putatively *Ruppia megacarpa* seeds alongside the *Ruppia tuberosa*. In some areas up to 30% of the seeds are those of *Ruppia megacarpa* (Waycott et al. 2022). Of importance is that not all of the aquatic macrophyte species were able to be identified with DNA based testing of samples from sites surveys in October 2020 (Lewis et al. 2022). In fact, in addition to the more common *Ruppia tuberosa* haplotype 2 and *Althenia cylindrocarpa* presence as observed in field samples, a second distinct *Ruppia tuberosa* haplotype 1 was present across many sites, as was a third *Ruppia* sp. haplotype, exhibiting sufficient genetic distinctiveness to be classified as another species. This third *Ruppia* sp. did not match to *Ruppia megacarpa* or *Ruppia polycarpa,* the other regionally present *Ruppia* species. Thus, cryptic taxonomic (species) diversity exists among these samples at this time.

Given the potential genetic bottleneck experienced over the period 2001–2010, the Ruppia Community could be inbreeding where the recovering populations may be derived from a limited seed source. The loss of the Ruppia Community from the Coorong during the low water levels and elevated salinities (2001–2010) was on a significant scale and concerns as to the genetic consequences of these losses were raised by the Ruppia Translocation project advisory group (Ryan 2015). The living plant populations were lost across the southern Coorong and the seed bank was depleted (Paton et al. 2015b). In addition, the source material for translocation of seed laden sediments was a single site, Lake Cantara (southern section, Figure 10).

Today, there are at least many millions or even billions of seeds present throughout the Coorong. Our recorded extent of distribution of more than 52 km and over 16 months (October 2020–December 2021) had a mean number of seeds of 1064 s.e. ± 39 m^{-2} (Lewis et al. 2022). Based on aerial survey mapping of the Ruppia Community distribution in 2020 (Waycott et al. 2020a) in the central section between The Needles and Parnka Point, and applying the mean number of seeds to the area mapped (Appendix A, Table A5), a total of 5.5 billion seeds could be distributed across this 13.8 km^2 area. If *Ruppia* sp. seeds were absent from the system in 2010 as observations and monitoring indicates (Paton 2010, Paton et al. 2015b), there is significant potential for seed production to have grown to these numbers through inbreeding over the past 10 years.

There are several key knowledge gaps associated with the genetic diversity and connectivity in the southern Coorong that are important for developing restoration action plans. The population level genetic diversity of the main species in the Coorong, and adjacent regions, would provide a basis for evaluating future inbreeding and priority seed sources. Broader scale assessment of genetic diversity in conjunction with habitat availability surveys would enhance options for developing climate ready seed sources and identifying potential additional donor sites for future intervention activities (Waycott et al. 2022).

4.5.3 Climate change and adaptation of the Ruppia Community

Significant emerging pressures on the Ruppia Community in the southern Coorong are the individual and combined impacts of reduced inflow, sea level rise and increased temperatures (e.g. Dunlop et al. 2022). All current realistic scenarios for the region including the Coorong are that there will be higher sea-levels and reduced water availability from the broader Murray–Darling catchment. Essentially it is expected that changes to rainfall patterns will lead to periods where the conditions experienced during the Millennium Drought re-occur, on shorter repeat cycles. Therefore, the subsequent low water levels, poor connectivity, salt and nutrient accumulation, extreme hyper salinity and increased nutrient availability in the southern Coorong would be expected to directly impact the Ruppia Community. However, higher sea-levels would increase water levels in the lagoons but would be expected to lead to changes in where the habitats and species occur. Given the time taken for the Ruppia Community to recover from the loss of its seed bank over the period 2001–2010, repeated cycles of similar conditions are likely to have an impact if water levels cannot be maintained. Associated with sea-level rise may be a shift to a lower overall salinity of the Coorong South Lagoon if oceanic water is more freely entering the system. The current Ruppia Community has very wide salinity tolerance at the southern end, however, the reduced likelihood of salinities above 90 g L^{-1} will likely favour algal species over the aquatic macrophytes where nutrient loads are high.

Other aquatic plant species present in the region but not in the main Coorong lagoons include species of varying salinity tolerance namely *Ruppia megacarpa*, *R. polycarpa*, *Zannichellia palustris*, *Althenia patentifolia*, *A. bilocularis*, and *Stuckenia pectinata*. The estuarine seagrass *Zostera muelleri* also is regularly collected around the Murray Mouth at the northern end of the Coorong, and has been recorded in the main lagoon at times in recent history (Lewis et al. 2022). The importance of population level genetic diversity to climate change adaptability has been discussed in the preceding section. However, all efforts should be made to identify and maintain adaptability in the aquatic macrophyte community with the climate challenge becoming more immediate and impactful (Pörtner et al. 2022).

Climate adaptation planning for the Ruppia community, when aligned to the overall restoration strategy for the Coorong ecosystem, will enable longer term ecological restoration actions to be identified. For example, if interventions to reduce nutrient loads leads to a more marine salinity regime rather than an extreme-hypersaline one, the species targeted for ecological restoration actions will change. In addition, if informed by the long term history of the site (Mosley et al. 2018) including the paleo history, traditional owner and local community values, and the role the Coorong has in the wider regional ecosystem, the functions and nature of the Coorong ecological community under different climate scenarios can be better predicted.

List of shortened forms and glossary

AHD	Australian height datum. Note: the mean sea level for 1966-1968 was assigned a value of 0.000 m on the Australian Height Datum (AHD) at 30 tide gauges around the coast of the Australian continent (Geosciences Australia).
Aquatic macrophyte	A submerged aquatic flowering plant, large enough to be seen by the naked eye.
Biomass	The total mass of sampled organisms, measured as wet or dry and for a particular sampled area such as m^{-2}.
Biota	
Central Coorong	In this report, the central part of the Coorong stretching from the Needles to Hack Point connecting the North Lagoon and the South Lagoon.
DPSIR	Drivers, pressures, state, impact, response (DPSIR) framework—internationally accepted approach for reporting on the environment e.g. (Patrício et al. 2016, Jackson 2017)
DW	Dry weight (of a sample).
Eutrophication	The increase in the supply of organic matter to an ecosystem. Eutrophic systems are typically characterised by excessive plant and algal growth due to the increased availability of one or more limiting plant growth factors needed for photosynthesis including light, carbon dioxide, and nutrients.
Filamentous algae	The green filamentous algal community which occurs in the Coorong, consisting of *Ulva paradoxa*, *Rhizoclonium sp*. and *Cladophora sp*. defined in Collier et al. 2017.
Haplotype	A specific combination of jointly inherited nucleotides or DNA markers from polymorphic sites in the same chromosomal segment such as the chloroplast.
Hyper-eutrophic	Undesirable state highly enriched with nutrients and algae, i.e. high chlorophyll a (>5 ug L^{-1}) and total nutrient concentrations (TN; >1 mg L^{-1} and TP >0.1 mg L^{-1}) concentration (Mosley and Hipsey 2019); (ANZECC 2000/2018, undesirable state highly enriched with nutrients and algae).
Hyper-salinity	Water having higher salinity than seawater
IQR	InterQuartile Range, a measure of statistical dispersion in descriptive statistics.
Life history stages	The different growth stages of an organism that reflect investments in growth, reproduction and survivorship. For *R. tuberosa*, an organism goes through during its lifetime, i.e. seed, seedling, vegetative growth of mature plant, flowering, fruiting, turion formation, senescing plant.
Macrophyte	An aquatic plant large enough to be seen by the naked eye, in this report specifically a flowering plant (angiosperm).
Mesotrophic	A body of water having a moderate or mid-range amount of dissolved nutrients.
Millennium Drought	The Millennium Drought occurred from 1996-2010 (Van Dijk et al. 2013), the impacts to the Coorong occurring over the period that El Niño was experienced across South Australia 2001-2010.
North Lagoon	As a region in this report we refer to the North Lagoon as the part of the Coorong from the Murray Mouth to the Needles. Literature elsewhere refer the North Lagoon as area from the Murray Mouth to Parnka Point.
Occupancy, Area of (AOO)	The area within its 'extent of occurrence', which is occupied by a taxon, excluding cases of vagrancy

Occupancy, Extent of (EOO)	The area contained within the shortest continuous imaginary boundary, which can be drawn to encompass all known, inferred or projected sites of present occurrence of a taxon, excluding cases of vagrancy.
ppt	Parts per thousand
Rapid Assessment Protocol (RAP)	Characterisation of sediment characteristics based solely on qualitative assessments of sediment colour, texture and odour, provides an informative and robust proxy for the degree and effects of sediment enrichment (Hallett et al. 2019).
Resilience	Resilience is the ability of the environment to withstand or recover from a shock or disturbance.
Ruppia Community	The multi species assemblage identified in this study that has become established across the southern Coorong and includes *Ruppia tuberosa*, *Althenia cylindrocarpa* along with an as yet unresolved species of *Ruppia*.
Salinity	Water salinity when measured by passing an electric current between the two electrodes of a salinity meter in water. Reported in various ways including Electrical conductivity (EC), Practical Salinity Units (psu), g kg^{-1} (or for water g L^{-1}) and equivalent to total dissolved solids (TDS) under come conditions depending on measurement. Salinity is temperature and the types of salt present in water. Salts increase the ability of a solution to conduct an electrical current, so a high EC value indicates a high salinity level. Commonly reported at ppt (parts per thousand), g kg^{-1} (or for water g L^{-1}). Historically salinity was calculated as *salinity=1.80655*chlorinity (ppt or* g kg^{-1}*)*
Sampling core 'Cores'	A standard core referred to will be a sampled taken that is 7.5 cm diameter and to a depth of 8 cm, including all above and below ground plant community as well as sediment. The device used to take a care is typically a cylinder (such as plumping pipe) with a mark made at 8 cm to indicate depth that can be pushed into the sediment to isolate the area to be sampled.
South Lagoon	In this report, the part of the Coorong south of Hack Point.
Southern Coorong	In this report, the section of the Coorong from Long Point in the North Lagoon to south of Salt Creek at Tea Tree Crossing.
Spatial	Refers to the dimension of space or area
Temporal	Refers to the dimension of time
TLM	The Living Murray
T&I	Trials and Investigations (associated with the Healthy Coorong, Healthy Basin program)
Turion	Reproductive structure that *R. polycarpa* (Type I) and *R. tuberosa* (Type I and Type II) produce underground that is capable of forming into a new plant. Type I turions form at the leaf base, while Type II turions form at the rhizome tip.

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Appendix A – Summary of ecological objectives for managing the Ruppia Community in the Coorong

Table A1. Ecological objectives and associated ecological targets relating to the Ruppia Community of the Murray Estuary and Coorong in the updated long-term watering plan (Department for Environment and Water 2020a).

Vegetation: Restore *Ruppia tuberosa* colonisation and reproduction in the Coorong at a regional and local scale.
1. Continuous distribution of *R. tuberosa* beds along a 50 km section of the southern Coorong (excluding outliers).
2. Within the abovementioned distribution, 80% of the monitored sites should have *R. tuberosa* plants present in winter and summer.
3. 50% of sites with *R. tuberosa* to exceed the local site indicators for a healthy *R. tuberosa* population.
4. Support a resilient *R. tuberosa* population with seed densities of 2000 seeds m^{-2} by 2019 and 50% of sites having 60% cover in winter and a seed bank of 10,000 seeds.m-2 by 2029 in the Coorong South Lagoon.
Water quality: Establish and maintain stable salinities in the lakes and a variable salinity regime in the Murray Estuary and Coorong
1. To support aquatic habitat: maintain a salinity gradient from 0.5 ppt (g L^{-1}) to 35 ppt (g L^{-1}) between the Barrages and Murray Estuary area, <45 ppt (g L^{-1}) in the North lagoon, and from 60 ppt (g L^{-1}) to 100 ppt (g L^{-1}) in the South lagoon.

Table A2. Ecological objectives and associated ecological targets relating to the Murray Estuary and Coorong in the Condition Monitoring Plan (Department for Environment and Water and Natural Resources 2017).

Submerged Aquatic Vegetation **Regional level** 1. Extent of occurrence (EOO) along the Coorong of 43 km, excluding outliers. 2. Area of occupation (AOO) – within the sampled distribution, 80% of sites have plants present in both winter and summer. 3. Population vigour (VIG) – 50% of sites with *Ruppia tuberosa* should exceed the local site levels for a vigorous population. 4. Resilience (RES) – 50% of sites should exceed 2,000 seeds m^{-2} (by 2019). Vegetation and Foodweb: Maintain or improve *Ruppia tuberosa* colonisation and reproduction **Local (site) level** [for a vigorous population] 1. At least 30% of cores (75 mm diam.) with *Ruppia tuberosa* plants in winter and summer. 2. At least 10 shoots per core (75 mm diam.) with *Ruppia tuberosa* in winter.
Vegetation and Foodweb: Maintain or improve *Ruppia tuberosa* colonisation and reproduction
3. At least 50% of surface sediment cores (75 mm diam. × 40 mm deep) with seeds. 4. At least 50 flower-heads m^{-2} for 50% of the area sampled with *Ruppia tuberosa* at a site during spring flowering. 5. At least 50% of cores (75 mm diam.) taken across the *Ruppia tuberosa* beds at the end of summer contain turions
Long-term resilience 1. By 2019: 2,000 seeds m^{-2} at 50% of sites (≥8 seeds per 75 mm diam. × 40 mm deep core). 2. By 2029: 10,000 seeds m^{-2} at 50% of sites (≥40 seeds per 75 mm diam. × 40 mm deep core).
Wetland habitat: Maintain or improve habitable sediment conditions in mudflats
1. Habitable sediments are occurring along the Murray Mouth and Coorong into the South Lagoon. 2. Sediments are maintained as fine to medium sands and are mostly moderately well sorted. 3. Sediment organic matter is maintained. 4. Sediments provide microphytobenthic food for the benthic food web.
Surface water regime: Maintain a permanent Murray Mouth opening through freshwater outflows to improve water quality and maximise connectivity
1. A minimum of 2,000 ML/day of water is discharged through the Lower Lakes barrages and fishways for 365 days. 2. Murray Mouth is open 100% of days in 95% of years as a result of freshwater releases from the barrages. 3. Where freshwater releases are not adequate to maintain an open Murray Mouth, the Mouth is maintained open for the remainder of the year as a result of dredging.

Table A3. Expected environmental outcomes that solely or in part were set for the CLLMM in the Basin Wide Environmental Watering Strategy (Murray–Darling Basin Authority 2022).

Native vegetation – Vegetation	A sustained and adequate population of *Ruppia tuberosa* in the south lagoon of the Coorong, including: 1. *Ruppia tuberosa* to occur in at least 80% of site across at least a 43 km extent 2. By 2029, the seed bank to be sufficient for the population to be resilient to major disturbance.

Table A4: Criteria used to define the status of *R. tuberosa* in the southern Coorong (Paton et al. 2015b, Paton et al. 2017b).

Scale	Criterion
Regional scale	R. 1 Extent of Occurrence (EOO)
	R. 2 Area of Occupation (AOO)
	R. 3 Population Vigour (VIG)
	R. 4 Population Resilience (RES)
Local scale	L.1 Population cover
	L. 2 Population (shoot) density
	L. 3 Reproductive output
	L. 4 Propagule (seed) density
	L. 5 Asexual reproduction
Future resilience	RS. 1 By 2019
	RS. 2 By 2029
Target	*Ruppia tuberosa* plants distributed along 43 km of the southern Coorong in winter and summer
	Ruppia tuberosa plants present at 80% of sites monitored within the EOO in winter and summer
	Vigorous *Ruppia tuberosa* populations at 50% of sites within the EOO where *R. tuberosa* present, where a vigorous population has at least 30% cover and at least 10 shoots per core (75 mm diam), for at least one depth
	At least 2,000 seeds m^{-2} at 50% of sites with *Ruppia tuberosa* (target set for 2019)
	At least 30% cover (live shoots) in winter and summer, for at least one depth
	At least 10 live shoots per core (75 mm diam) in winter and summer, for at least one depth
	At least 50 flower-heads m^{-2} during spring flowering, for at least one depth
	At least 50% of cores (75 mm diam) taken across the *Ruppia tuberosa* beds in late summer containing seeds
	At least 50% of cores (75 mm diam) taken across the *Ruppia tuberosa* beds in late summer containing turions
	2,000 seeds m^{-2} at 50% of sites [> 8 seeds per core (75 mm diam. x 4 cm deep)]
	10,000 seeds m^{-2} at 50% of sites [> 40 seeds per core (75 mm diam. x 4 cm deep)]

Table A5: Seed bank estimates for regional scale comparisons. Based on data from the central section defined by the area: northern limit 35°50’21.54”S 139°21’47.49”E (-35.839317° 139.363192°), southern limit 36° 9’21.21”S 139°37’29.79”E (-36.155892° 139.624942°) (Waycott et al. 2020a), ^Seed number km^{-2} = 1,259,000,000, seed weight on average 0.475 mg for *Ruppia tuberosa*.

Community type	Description	Area mapped as Ruppia Community Type (km^2) [Dec 2019/Jan 2020]	Patchiness (proportion of area)	Seed total across area mapped^	Seed weight total*
Ruppia / algal mat Community type I	Heavily algal infested	3.8	0.5	2,392,100,000	
Ruppia / algal mat Community type II	Patchily algal infested	9.8	0.25	3,084,550,000	
Ruppia Community type III	No visible algae	0.2	0.1	25,180,000	
Summary totals		13.8	Estimate for central section	5,501,830,000 (i.e. 5.5 billion)	2,613,369 g (i.e. 2.57 tonnes)

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