Chapter 3
Seagrasses of Southern and South-Western Australia

Kieryn Kilminster, Renae Hovey, Michelle Waycott and Gary A. Kendrick

Abstract The coastal waters of southern and south-western Australia are home to almost 30,000 km^2 of seagrass, dominated by temperate endemic species of the genera *Posidonia* and *Amphibolis.* In this region, seagrasses are common in estuaries and sheltered coastal areas including bays, lees of islands, headlands, and fringing coastal reefs. Additionally, extensive meadows exist in the inverse estuaries of the Gulfs in South Australia, and in Shark Bay in Western Australia. This chapter explores (i) how geological time has shaped the coastline and influenced seagrasses, (ii) present day habitats and drivers, (iii) how biogeography patterns previously reported have been altered due to anthropogenic and climate impacts, and (iv) emerging threats and management issues for this region. Species diversity in this region rivals those of tropical environments, and many species have been found more than 30 km offshore and at depths greater than 40 m. Seagrasses in this region face a future of risk from multiple stressors at the ecosystem scale with

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coastal development, eutrophication, extreme climate events and global warming. However, our recent improved understanding of seagrass recruitment, restoration and resilience provides hope for the future management of these extraordinary underwater habitats.

3.1 Introduction

The diverse and expansive seagrass meadows of southern and south-western Australia create stunning underwater landscapes. Seagrasses in this region are recognised as a temperate biodiversity hotspot, with species diversity rivalling those of tropical environments (Carruthers et al. 2007). From Shark Bay to the western edge of the Great Australian Bight, seagrasses occupy an estimated 20,000 km^2 (Walker 1991). The coastal waters of South Australia are home to an additional 9,612 km^2 with more than 80% of this seagrass found within the Spencer Gulf (5,520 km^2) and the Gulf of St Vincent (2,440 km^2) (Edyvane 1999). These temperate meadows are often dominated by endemic *Posidonia* and *Amphibolis* species with high biomass (Fig. 3.1).

Species distributions are broadly known in South Australia (see Chap. 1 and the Appendix of this volume for genus distributions, plus Shepherd and Robertson 1989; Kirkman 1997). *Posidonia* is the dominant genus in terms of spatial coverage, with *P. angustifolia*, *P. australis*, and *P. sinuosa* being the most abundant species within the genus. The upper parts of both Spencer Gulf and Gulf St Vincent

Fig. 3.1 Southern Fiddler ray within a *Posidonia sinuosa* meadow at Rottnest Island, Western Australia

have extensive tidal flats that are dominated by *P. australis* and *Zostera/Heterozostera* species (for current status of *Heterozostera* see the Appendix of this volume). Within the gulfs and bays around South Australia, seagrasses are generally restricted to depths of <20 m (Shepherd and Robertson 1989; Edyvane 1999). However, in the clearer waters of Investigator Strait, some offshore islands, and at the base of cliffs on the west coast of Eyre Peninsula, seagrasses grow to depths of 30 m or more (Shepherd and Robertson 1989).

In temperate Western Australia, seagrasses occupy shallow coastal habitat (Walker 1991), in water depths ranging from the intertidal to >50 m. Seagrasses occur in a range of habitats from wave-exposed sandbanks to sheltered bays, lagoons and estuaries (Carruthers et al. 2007). They grow predominantly on sand from 1 to 35 m depth (Cambridge and Kuo 1979), but also on deep rock to over 50 m deep (e.g. *Thalassodendron pachyrhizum*), and shallow estuarine mud and sand flats. Across southern temperate Australia, *Halophila australis* is endemic and is likely the only *Halophila* species occurring across the region immediately to the east of the Great Australian Bight, to Tasmania.

Along the southwest coast of Australia, seagrass habitats are heavily influenced by exposure to ocean swells and large-scale sand movement. *Amphibolis griffithii* has higher water baffling capacity than *Posidonia australis*, *P. sinuosa* or mixed *Posidonia* meadows (van Keulen and Borowitzka 2002). *Amphibolis antarctica* meadows have been shown to reduce water flows from 50 to 2–5 cm s^{-1} (Verduin and Backhaus 2000). The *P. ostenfeldii* group of species typically form patchy meadows with mixed species in open-ocean or rough water sublittoral habitats (Campey et al. 2000). They are characterised by their long, thick, leathery leaves and long leaf sheaths that are deeply buried. Their ability to withstand ocean swell is because, unlike the *Posidonia australis* group, their rhizomes grow vertically instead of horizontally. These characters appear to be associated with strong wave movement and mobile sand substratum typical of the environments in which they are found (Kuo and Cambridge 1984).

The distribution of seagrasses around Australia was described in Larkum et al. (1989). Rather than revisit this earlier work on biogeography, which has remained relatively unchanged for this region, we explore aspects of new knowledge which now shape our understanding of seagrasses of southern and south-western Australia.

Specifically this chapter will describe:

(i) how geological time has shaped the coastline and influenced seagrasses,
(ii) present day seagrass habitats and drivers,
(iii) anthropogenic and climate change pressures which have altered biogeography patterns previously reported, and
(iv) emerging threats and management issues for this region.

Several case studies are discussed within this chapter, and Fig. 3.2 provides a map of seagrass in each of these locations.

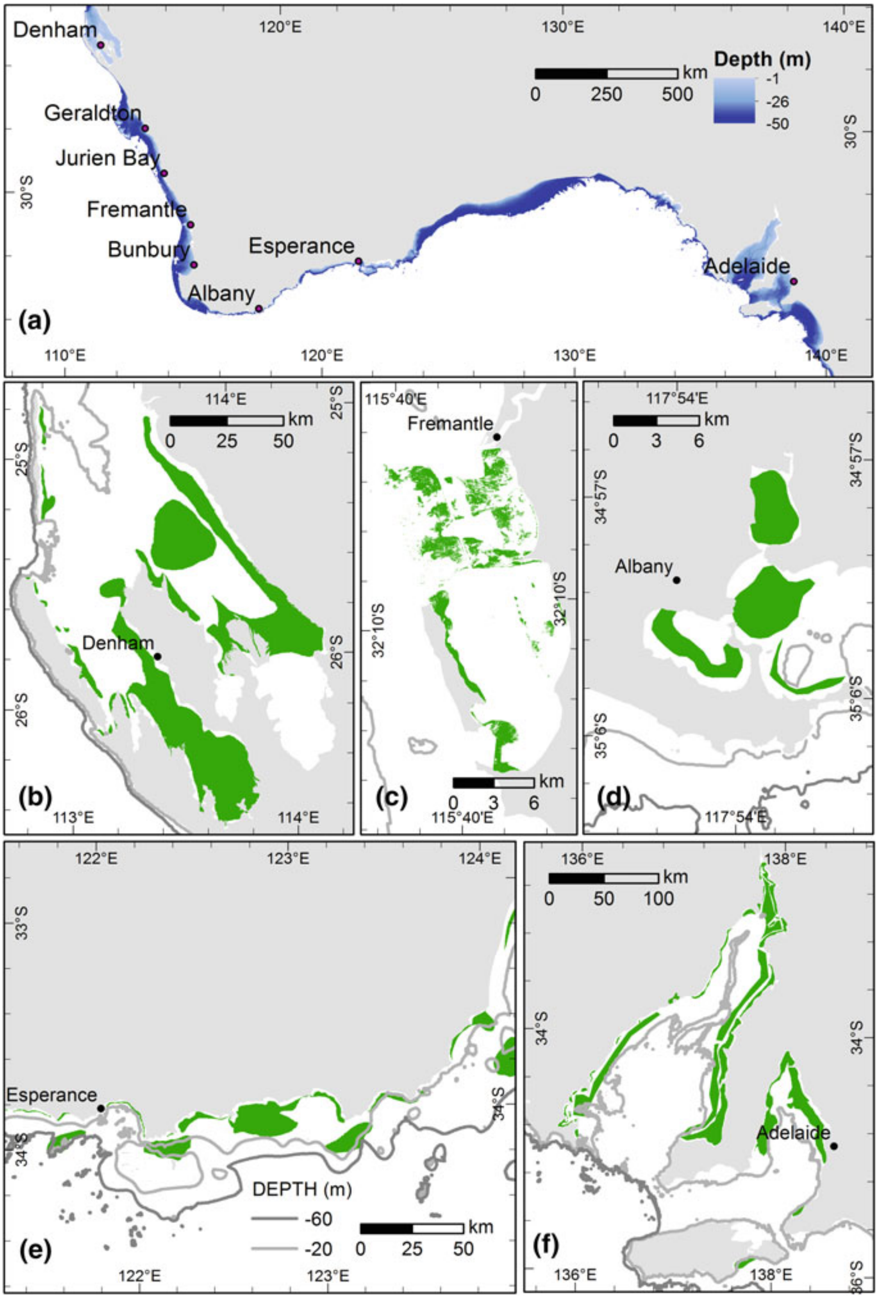


Fig. 3.2 Map of region and case-study areas. **a** Potential areas in southern and south-western where water depth is likely to be suitable for seagrass habitat, and seagrass distribution in **b** Shark Bay, **c** Owen Anchorage and Cockburn Sound, **d** Albany harbours, **e** Recherche Archipelago and, **f** Gulf of St Vincent and Spencer Gulf

3.2 The Forces Shaping Seagrasses and the Coastline over Geological Time

Modern day lineages of seagrasses evolved some 60 + million years ago (Waycott et al. 2018, Chap. 5, this volume). Since this time, global sea level has fluctuated significantly, however seagrasses have been able to adapt to the rate of change in sea level (Orth et al. 2006). The modern day coastline of southern and south-western Australia became stable approximately 5,000 years ago (Fig. 3.3).

Rottnest Island, approximately 10 nautical miles offshore from Fremantle in Western Australia provides an excellent example of how the changing coastline has created habitats for seagrass. Rottnest Island is comprised of coastal Quaternary carbonate Aeolian dune complex and was joined to the mainland some 7,000 years ago. There are multiple drowned shorelines creating shoreline parallel ridges and reefs between Rottnest and the present-day Western Australian coast, and these sedimentary successions are very sensitive to erosion and sediment reworking (Richardson et al. 2005; Brooke et al. 2014). Sheltered waters provided by these reefal systems have favoured seagrasses with *Posidonia* and *Amphibolis* species forming patchy to continuous meadows, while seagrasses with reinforced fibres in their leaves (*P. ostenfeldii* complex) or wiry stems (*Amphibolis* species) dominate in more exposed waters (Carruthers et al. 2007). The high endemism of seagrasses in this region perhaps reflects the tectonic and geological stability of the region over the last 50 million years or so, allowing specialisation of seagrasses to occur.

The local Aboriginals, the Nyoongar people, have cultural narratives which describe the sea level rise which occurred separating Rottnest (or *Wadjemup*) from the mainland (Robertson et al. 2016). Similar stories exist in South Australia for the Jaralde people regarding Kangaroo Island and the Narrangga people regarding Spencer Gulf, likely to be associated with sea level rises between 10 and 12,000 years ago (Reid et al. 2014).

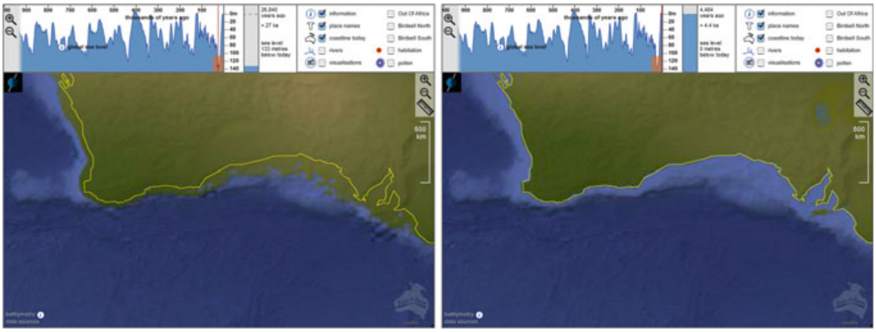


Fig. 3.3 Coastline of south-west Australia approximately 27,000 years ago (left) and coastline stabilised approximately 5,000 years ago to current position (right) (Images from http://sahultime.monash.edu.au)

Seagrasses have themselves altered this coastline by the in situ generation and trapping of carbonate sediments, derived in part from the calcareous algal epiphytes living on seagrass blades. This is one aspect which have earned seagrasses the title of 'ecosystem engineers'—sensu Jones et al. (1997). A study of the coast in Geraldton, Western Australia revealed fine modern skeletal sands within 2 km of shore were dominated by modern bioclasts (Fig. 3.4) living in association with seagrass meadows (Tecchiato et al. 2016). The Australian coast was divided into three major sediment provinces by Short (2010), with the south and west coast described as carbonated-dominated. Carbonate sediment makes up approximately 70% of the beach sand in this region, with the exception of the south-western tip from Augusta to Bremer Bay, where carbonate sediments were approximately 30% (Short 2010). Calcareous sediments, made up of skeletal remains of bivalves, benthic foraminifera, bryozoans, coralline algae and echinoids, also dominate within Spencer Gulf in South Australia (O'Connell et al. 2016).

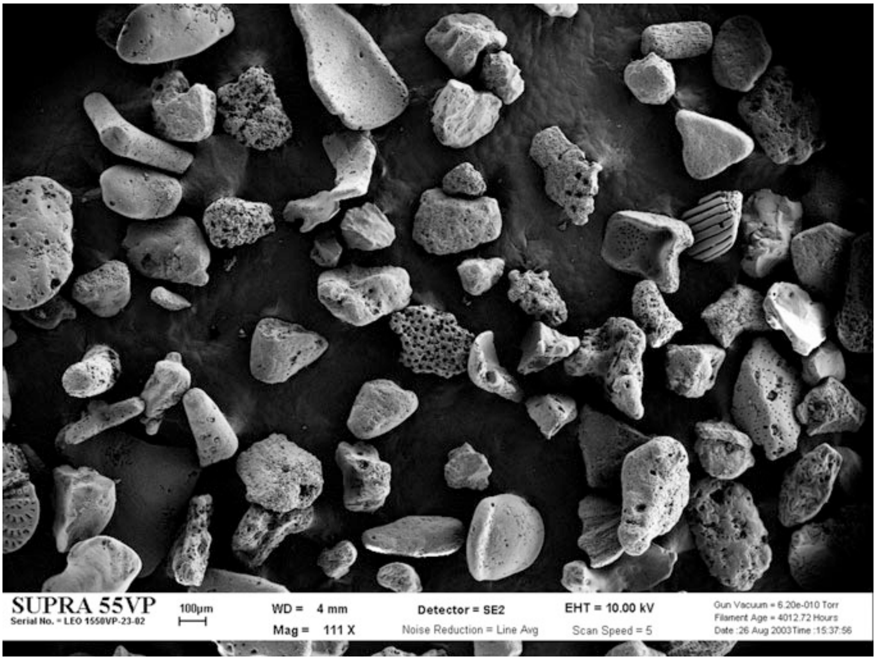


Fig. 3.4 Sediment grains from Western Australia viewed by scanning electron microscopy at 111 × magnification clearly showing skeletal makeup of the coastal sands

3.3 Present Day Seagrass Habitats and Drivers

Seagrasses in southern and south-western Australian waters play important roles providing habitat for many fish and crustaceans, including commercially and recreationally important species such as King George whiting (Connolly 1994; Connolly and Jones 1996; Connolly et al. 1999; Hyndes et al. 1999; Bryars 2003; Bloomfield and Gillanders 2005). They support a large range of biodiversity, including molluscs, and epiphytic plants and algae (Keough and Jenkins 1995), and stabilize coastal sediments, trapping sediments, and preventing coastal erosion (Keough and Jenkins 1995; Westphalen et al. 2004). Carbon export from seagrass meadows to adjacent habitats may act as ecological subsidies (Connolly et al. 2005; Hyndes and Lavery 2005) and recently, attention has been given to their role in carbon burial and sequestration (Fourqurean et al. 2012; Lavery et al. 2013; Serrano et al. 2014; Marbà et al. 2015).

Seagrasses grow on sediments in intertidal and subtidal waters, wherever sufficient light and favourable hydrodynamic conditions exist. In this region, seagrasses are common in estuaries and sheltered coastal areas including bays, lees of islands, headlands, and fringing coastal reefs (Carruthers et al. 2007). The inverse estuaries of the Gulfs in South Australia, or in Shark Bay in Western Australia are also home to extensive seagrass meadows (Walker et al. 1988; Edyvane 1999).

Carruthers et al. (2007) described seagrass habitats for south-west and south-coast Western Australia as ‘sheltered’, ‘exposed’ and ‘estuarine’ habitats. This habitat classification is extended to South Australian waters with the inclusion of ‘inverse estuary’ to account for the habitats found within the gulfs. Table 3.1 provides a description of habitat type with seagrass assemblages commonly found in each region. Conceptual diagrams (Figs. 3.5, 3.6 and 3.7) present this information diagrammatically. Note, the natural break in the habitat types occurs at the Great Australian Bight, so is not explicitly described by State boundaries. The majority of seagrasses in the marine environments of south and south-western Australia are described as enduring, persistent seagrass meadows, while those in estuarine environments, particularly the bar-built estuaries, may have a mix of transitory, colonising seagrass meadows (sensu Kilminster et al. 2015). Dominant meadow types are also provided in Table 3.1 for each habitat found with these regions.

The sheltered waters of southern and south-western Australia are usually dominated by *Posidonia* and *Amphibolis* spp., both forming large, dense, enduring meadows. On the south-west coast, *Halophila ovalis*, *H. decipiens*, *Heterozostera nigricaulis*, *H. polychlamys*, and even sometimes *Syringodium isoetifolium* tend to occur as an understory to the larger-bodied seagrasses (Kendrick et al. 1999; Carruthers et al. 2007), and they may be first to recolonise sediments from blowouts following storms (Kirkman and Kuo 1990) or boat mooring damage (Walker et al. 1989). In southern Australia, sheltered waters are usually dominated by *P. australis*, while in deeper waters *P. sinuosa*, *P. angustifolia*, *A. antarctica* and *A. griffithii* are present (Edyvane 1999).

Table 3.1 Description of habitat types and commonly found seagrass assemblages within each sub-region of southern and south-western Australia

Region	Exposure and type	Sediment type	Seagrass assemblages (dominant meadow forming species in bold)	Dominant species type	Dominant meadow form	Example locations
South-west WA	Embayment	Carbonate	***Amphibolis antarctica*** ***Amphibolis griffithii*** ***Posidonia australis*** ***Posidonia sinuosa*** *Syringodium isoetifolium* *Halophila ovalis* *Halophila australis* *Halophila decipiens* *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring	Safety Bay, Geographe Bay, Cockburn Sound
South-west WA	Exposed coastline	Carbonate	***Amphibolis antarctica*** ***Amphibolis griffithii*** ***Posidonia australis*** ***Posidonia coriacea*** ***Posidonia sinuosa*** *Posidonia angustifolia* *Thalassodendron pachyrhizum* *Halophila ovalis* *Halophila australis* *Halophila decipiens* *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring, rarely transitory	Marmion Marine Park, Jurien Marine Park, Owen Anchorage
South-west WA	Sheltered estuary	Silicate	***Halophila ovalis*** ***Ruppia megacarpa*** *Zostera mulleri* *Posidonia australis* *Halophila decipiens*	Colonising	Enduring and transitory	Swan-Canning, Peel-Harvey Leschenault

(continued)

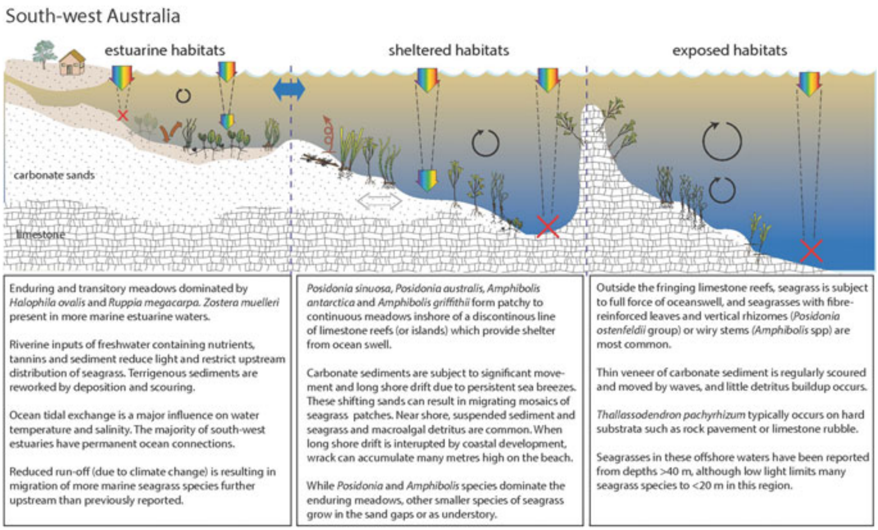
Table 3.1 (continued)

Region	Exposure and type	Sediment type	Seagrass assemblages (dominant meadow forming species in bold)	Dominant species type	Dominant meadow form	Example locations
South Coast WA	Embayment	Silicate	***Amphibolis antarctica*** ***Amphibolis griffithii*** ***Posidonia sinuosa*** ***Posidonia ostenfeldii* complex** *Posidonia australis* *Posidonia angustifolia* *Halophila ovalis* *Halophila australis* *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring	King George Sound, Two Peoples Bay
South Coast WA	Exposed coastline	Carbonate	***Amphibolis antarctica*** ***Amphibolis griffithii*** ***Posidonia sinuosa*** ***Posidonia australis*** ***Posidonia angustifolia*** ***Posidonia ostenfeldii* complex** *Thalassodendron pachyrhizum* *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring	Esperance
South Coast WA	Sheltered estuary	Silicate	***Ruppia megacarpa*** ***Posidonia australis*** *Posidonia sinuosa* *Amphibolis antarctica* *Amphibolis griffithii* *Halophila australis* *Halophila ovalis* *Halophila decipiens* *Zostera mulleri*	Persistent, opportunistic and colonising	Enduring and transitory	Oyster Harbour, Walpole-Nornalup, Wilson Inlet, Oyster Harbour

(continued)

Table 3.1 (continued)

Region	Exposure and type	Sediment type	Seagrass assemblages (dominant meadow forming species in bold)	Dominant species type	Dominant meadow form	Example locations
South Coast SA	Sheltered inverse estuary	Carbonate	***Posidonia australis*** ***Posidonia angustifolia*** *Amphibolis antarctica* *Amphibolis griffithii* *Heterozostera nigricaulis* *Halophila australis*	Persistent	Enduring	Upper Gulf of St Vincent, Upper Spencer Gulf
South coast SA	Disconnected embayment/ estuary	Silicate	***Ruppia megacarpa*** ***Ruppia tuberosa*** *Zostera muelleri*	Colonising	Transitory and enduring	The Coorong
South coast SA	Embayment	Carbonate	***Posidonia australis*** ***Posidonia sinuosa*** ***Posidonia angustifolia*** ***Amphibolis antarctica*** ***Amphibolis griffithii*** *Halophila australis* *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring	Adelaide waters, Emu Bay, Fowlers Bay
South coast SA	Exposed coastline	Carbonate	***Amphibolis antarctica*** ***Amphibolis griffithii*** ***Posidonia australis*** ***Posidonia angustifolia*** ***Posidonia ostenfeldii* complex** *Heterozostera nigricaulis* *Heterozostera polychlamys*	Persistent and opportunistic	Enduring	Offshore island—Pearson Island, Flinders Island



Enduring and transitory meadows dominated by *Halophila ovalis* and *Ruppia megacarpa*. *Zostera muelleri* present in more marine estuarine waters.

Riverine inputs of freshwater containing nutrients, tannins and sediment reduce light and restrict upstream distribution of seagrass. Terrigenous sediments are reworked by deposition and scouring.

Ocean tidal exchange is a major influence on water temperature and salinity. The majority of south-west estuaries have permanent ocean connections.

Reduced run-off (due to climate change) is resulting in migration of more marine seagrass species further upstream than previously reported.

Posidonia sinuosa, *Posidonia australis*, *Amphibolis antarctica* and *Amphibolis griffithii* form patchy to continuous meadows inshore of a discontinous line of limestone reefs (or islands) which provide shelter from ocean swell.

Carbonate sediments are subject to significant movement and long shore drift due to persistent sea breezes. These shifting sands can result in migrating mosaics of seagrass patches. Near shore, suspended sediment and seagrass and macroalgal detritus are common. When long shore drift is interupted by coastal development, wrack can accumulate many metres high on the beach.

While *Posidonia* and *Amphibolis* species dominate the enduring meadows, other smaller species of seagrass grow in the sand gaps or as understory.

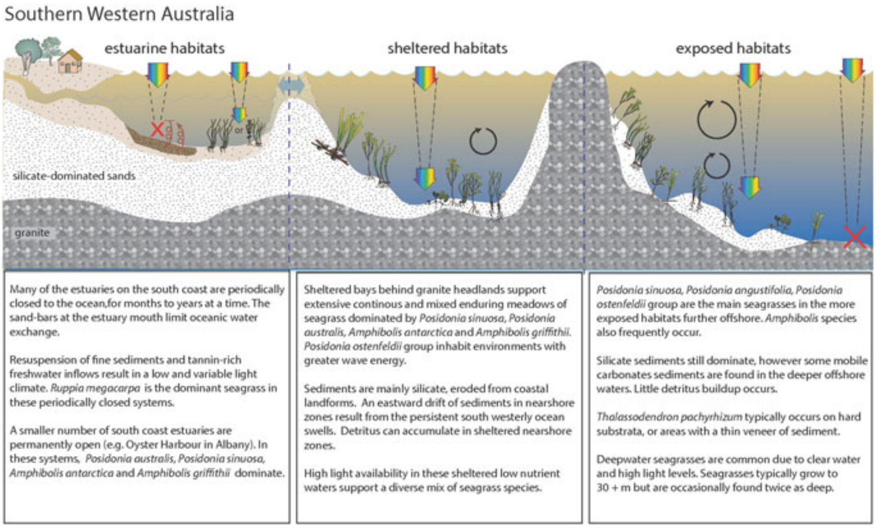
Outside the fringing limestone reefs, seagrass is subject to full force of oceanswell, and seagrasses with fibre-reinforced leaves and vertical rhizomes (*Posidonia ostenfeldii* group) or wiry stems (*Amphibolis* spp) are most common.

Thin veneer of carbonate sediment is regularly scoured and moved by waves, and little detritus buildup occurs.

Thallassodendron pachyrhizum typically occurs on hard substrata such as rock pavement or limestone rubble.

Seagrasses in these offshore waters have been reported from depths >40 m, although low light limits many seagrass species to <20 m in this region.

Fig. 3.5 Seagrass habitats in south-west Australia



Many of the estuaries on the south coast are periodically closed to the ocean,for months to years at a time. The sand-bars at the estuary mouth limit oceanic water exchange.

Resuspension of fine sediments and tannin-rich freshwater inflows result in a low and variable light climate. *Ruppia megacarpa* is the dominant seagrass in these periodically closed systems.

A smaller number of south coast estuaries are permanently open (e.g. Oyster Harbour in Albany). In these systems, *Posidonia australis*, *Posidonia sinuosa*, *Amphibolis antarctica* and *Amphibolis griffithii* dominate.

Sheltered bays behind granite headlands support extensive continous and mixed enduring meadows of seagrass dominated by *Posidonia sinuosa*, *Posidonia australis*, *Amphibolis antarctica* and *Amphibolis griffithii*. *Posidonia ostenfeldii* group inhabit environments with greater wave energy.

Sediments are mainly silicate, eroded from coastal landforms. An eastward drift of sediments in nearshore zones result from the persistent south westerly ocean swells. Detritus can accumulate in sheltered nearshore zones.

High light availability in these sheltered low nutrient waters support a diverse mix of seagrass species.

Posidonia sinuosa, *Posidonia angustifolia*, *Posidonia ostenfeldii* group are the main seagrasses in the more exposed habitats further offshore. *Amphibolis* species also frequently occur.

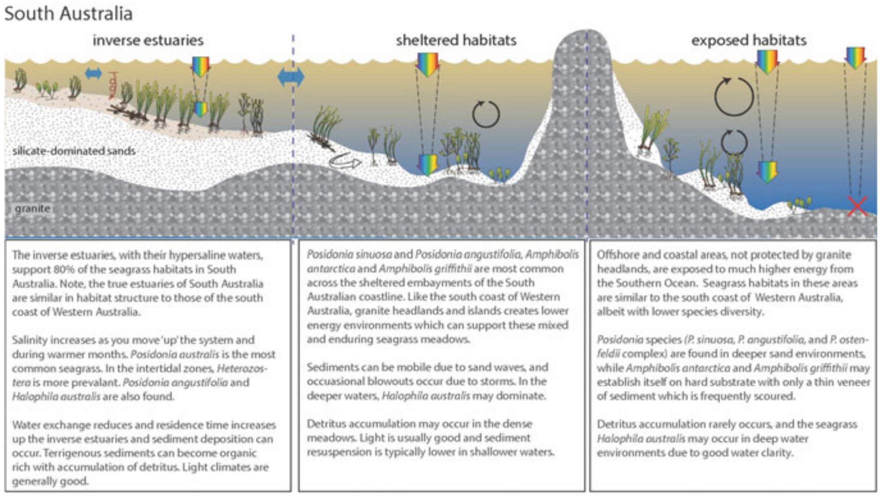
Silicate sediments still dominate, however some mobile carbonates sediments are found in the deeper offshore waters. Little detritus buildup occurs.

Thalassodendron pachyrhizum typically occurs on hard substrata, or areas with a thin veneer of sediment.

Deepwater seagrasses are common due to clear water and high light levels. Seagrasses typically grow to 30 + m but are occasionally found twice as deep.

Fig. 3.6 Seagrass habitats in southern Australia, from Cape Leeuwin to Spencer Gulf

Enduring *Posidonia* and *Amphibolis* spp. still feature in the exposed waters of southern and south-western Australia, however those *Posidonia* species more tolerant of rough conditions, such as *P. coriacea* and the *P. ostenfeldii* complex, may form patchy meadows (Campey et al. 2000; Carruthers et al. 2007). Western



The inverse estuaries, with their hypersaline waters, support 80% of the seagrass habitats in South Australia. Note, the true estuaries of South Australia are similar in habitat structure to those of the south coast of Western Australia.

Salinity increases as you move 'up' the system and during warmer months. *Posidonia australis* is the most common seagrass. In the intertidal zones, *Heterozostera* is more prevalant. *Posidonia angustifolia* and *Halophila australis* are also found.

Water exchange reduces and residence time increases up the inverse estuaries and sediment deposition can occur. Terrigenous sediments can become organic rich with accumulation of detritus. Light climates are generally good.

Posidonia sinuosa and *Posidonia angustifolia*, *Amphibolis antarctica* and *Amphibolis griffithii* are most common across the sheltered embayments of the South Australian coastline. Like the south coast of Western Australia, granite headlands and islands creates lower energy environments which can support these mixed and enduring seagrass meadows.

Sediments can be mobile due to sand waves, and occuasional blowouts occur due to storms. In the deeper waters, *Halophila australis* may dominate.

Detritus accumulation may occur in the dense meadows. Light is usually good and sediment resuspension is typically lower in shallower waters.

Offshore and coastal areas, not protected by granite headlands, are exposed to much higher energy from the Southern Ocean. Seagrass habitats in these areas are similar to the south coast of Western Australia, albeit with lower species diversity.

Posidonia species (*P. sinuosa*, *P. angustifolia*, and *P. ostenfeldii* complex) are found in deeper sand environments, while *Amphibolis antarctica* and *Amphibolis griffithii* may establish itself on hard substrate with only a thin veneer of sediment which is frequently scoured.

Detritus accumulation rarely occurs, and the seagrass *Halophila australis* may occur in deep water environments due to good water clarity.

Fig. 3.7 Seagrass habitats in southern Australia, from Spencer Gulf to the east

Australian waters have greater *Posidonia* species diversity than South Australia. The deeper waters of the South Australian coast are typically home to *P. sinuosa*, and *P. angustifolia* (and *A. antarctica* and *A. griffithii*) (Edyvane 1999).

In the inverse estuaries (large gulfs) of South Australia the tidal range is much greater (up to 3.6 m) than the microtidal tides typical of the region, and tides within the gulfs are typified by periods of minimal tidal movement (termed a 'dodge' tide) (*also see the Shark Bay text box for an example in Western Australia*). These waters are also hypersaline, with mean salinities of 42–49 ppt in North Spencer Gulf and 35–42 ppt in Gulf of St Vincent (Edyvane 1999). These conditions create sheltered intertidal seagrass habitats dominated by *Heterozostera*.[1] Enduring meadows of *Posidonia australis* dominate the sheltered subtidal areas, and in the deeper gulf waters, *P. sinuosa*, *P. angustifolia* and *A. antarctica* are common. *Posidonia ostenfeldii* complex can form small communities in more exposed waters and *Halophila australis* has been found as deep as 23 m in offshore gulf waters (Edyvane 1999).

Estuarine waters are home to just a few of the seagrasses found in the region, likely due fewer species being tolerant to the frequent large swings in salinity. In the south-west estuaries with permanent connections to the ocean, monospecific meadows of *Halophila ovalis* usually dominate. In these estuaries, *Halophila decipiens* can co-occur with *H. ovalis* or occur by itself (Kuo and Kirkman 1995). *Zostera muelleri* tends to be found close to the mouth of the estuary, where salinity is more marine and fluctuates less. Interestingly, *Posidonia australis* has recently

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[1] Note historical reports of *Zostera tasmanica* e.g. Edyvane (1999), have been interpreted as *Heterozostera nigricaulis*, based on Kuo (2005).

been observed in the Swan-Canning estuary (M. Sanchez-Alarcon, V. Forbes pers. comm, 15 Dec 2015) associated with reduced rainfall and streamflow in the catchment (Petrone et al. 2010; Silberstein et al. 2012). *Ruppia megacarpa* is the most common seagrass in the occasionally open bar-built estuaries of the south-coast, such as Wilson Inlet (Carruthers et al. 1999, 2007). *Posidiona australis*, *P. sinuosa*, *Amphibolis antarctica* and *A. griffithii* can be found in a few of the permanently open estuaries on the south-coast, such as Oyster Harbour and Waychinicup, where large connections to the ocean ensure good marine water exchange. Hydrological modifications and water abstraction from the River Murray has altered the seagrass ecology of the Coorong in South Australia and resulted in the substantial reduction in area of both *Ruppia megacarpa* and *Ruppia tuberosa* (McKirdy et al. 2010; Whipp 2010; Dick et al. 2011).

Geomorphological differences between the south-west of Western Australia and south coast of Western Australia and South Australia create a range of different seagrass habitats. Exposure is thought to be a key factor influencing not only what seagrasses can prevail, and may also be a proxy for other ecological aspects. For example, the genetic diversity of *Posidonia australis* is greater in more open waters than inshore sites which have low water movement and/or face strong prevailing winds at the time of seed dispersal (Sinclair et al. 2014). Light and nutrient availability also influence seagrass habitats in this region (Cambridge and Hocking 1997; Collier et al. 2007; Lee et al. 2007; Ralph et al. 2007).

Hydrodynamic conditions are a significant driver of seagrass habitats across multiple scales. At the largest of these scales, the Leeuwin Current system (including the Capes Current and Creswell Currents) and Flinders Current provide dispersal and connectivity opportunities for seagrasses in this region. For example, floating fruit of *Posidonia australis*, moved by either currents or local winds, has the potential to regularly connect meadows 10s of kilometres apart, and occasionally connect meadows 100s of kilometres apart (Ruiz-Montoya et al. 2015). This effect is species dependent however, as the different fruiting and seed strategy and morphology alter their dispersal modes and capabilities (Ruiz-Montoya et al. 2012).

The two large gulfs of South Australia, Gulf St Vincent (6,800 km^2) and Spencer Gulf (ca. 22,000 km^2), are often categorised as inverse estuaries (Kämpf 2014). The large scale water movements into and out of these systems are strongly seasonal (Middleton et al. 2013; O'Connell et al. 2016). Within Spencer Gulf, where the most detailed analysis of water movement has been conducted (Middleton et al. 2013), essentially water movement remains within the gulf during the summer months with a nearshore northward water movement pattern. The winter pattern of current movement in Spencer Gulf leads to exchange with the oceanic waters outside the gulf and there is a stronger mixing across the gulf, east to west. As a result, during the warmer summer months, the period of propagules dispersal for many species especially *Posidonia*, a higher proportion of floating seeds would be retained within the system. In cooler months, the movement of *Amphibolis* seedlings occurs and these would be able to be transported further within and outside the Spencer Gulf system.

At the meadow scale, hydrodynamics affects the species of seagrass found within each habitat type. Seagrasses exposed to strong ocean swells (such as the southwest coast of Australia), appear to have adaptations to allow them to cope with significant drag forces (de los Santos et al. 2012, 2016). Both *Amphibolis griffithii* and *Amphibolis antarctica* meadows effectively baffle water flow, and *A. antarctica has* been shown to reduce water flows from 50 to 2–5 cm s^{-1} (Verduin and Backhaus 2000). Additionally, the wiry stems of these species may provide further protection from strong water movement. Similarly, *P. ostenfeldii* group of species typically form patchy meadows with mixed species in open-ocean or rough water (Campey et al. 2000). They are characterised by their long, thick, leathery leaves and long leaf sheaths that are deeply buried, and vertical rhizome growth. These characteristics appear to be associated with strong wave energy as well as highly mobile sand substratum, typical of the environments in which the *P. ostenfeldii* seagrasses are found (Kuo and Cambridge 1984).

Marine waters in southern and south-western Australia are considered oligotrophic, with nitrate concentrations <1 μM (Pearce and Pattiaratchi 1999; Balzano et al. 2015). In addition, carbonate sediment prevalent through much of the region, adsorbs phosphate onto calcium carbonate particles (McGlathery et al. 1994). These low nutrient waters tend to result in water with high clarity, allowing light to penetrate deeply. Seagrasses in this region are commonly found in waters greater than 30 m deep, and sometimes significantly deeper (see information box *Deepwater Seagrass in Temperate Southern Waters*).

With such low nutrient concentrations in the overlying water, the abundance of dense, highly productive seagrasses in this region has seemed paradoxical. How nutrient availability might influence seagrass habitats has been explored in the south-western Australian region over recent decades. For example: nutrient concentrations differed for *Posidonia coriacea* and *Heterozostera tasmanica* growing on the same carbonate sediments in Success Bank (Walker et al. 2004), suggesting species-specific differences in the nutrient requirements or the strategy of nutrient uptake and reallocation. Both Cambridge and Hocking (1997) and Collier et al. (2010) demonstrated that nutrient reabsorption and translocation from older plant tissues contributed to the nutrient requirement for *Posidonia sinuosa* and *Posidonia australis*. The addition of N+P to a *P. australis* meadow at Rottnest Island did not enhance growth, shoot density or biomass within 4 months of fertilization (Udy and Dennison 1999), while fertilization (N, N+P, P and Fe-EDTA) had mixed results that appeared site specific for transplanted seagrass shoots of *Posidonia australis* in the Albany Harbours (Cambridge and Kendrick 2009). We now know that rather than seagrass growth being highly constrained by the low nutrient waters, seagrasses in these regions contribute significant carbon (and nutrients) across ecosystem boundaries (Hyndes et al. 2014). Seagrass wrack is deposited at high rates on temperate south and south-western beaches (Kirkman and Kendrick 1997), and this wrack supports detrital consumers in both terrestrial and marine ecosystems (Ince et al. 2007; Heck et al. 2008). This detrital cycle seems highly important for the ecoregion.

Table 3.2 Range in depths where seagrasses have been observed or collected from Western and South Australia

Species	Depth range (m)	Reference
Halophila ovalis	0.1–38	Hillman et al (1995) Huisman et al. (1999)
Heterozostera nigricaulis	0.5–16.9	Kuo (2005)
Heterozostera polychlamys	2–48	Kuo (2005)
Posidonia australis	0.1–15	Cambridge and Kuo (1979)
Posidonia sinuosa	0.1–15	Cambridge and Kuo (1979)
Posidonia angustifolia	2–44	Cambridge and Kuo (1979) Huisman et al. (1999)
Posidonia ostenfeldii	5–20	Kuo and Cambridge (1984)
Posidonia coriacea	1–30	Kuo and Cambridge (1984)
Posidonia denhartogii	1–10	Kuo and Cambridge (1984)
Posidonia robertsoniae	0.5–20	Kuo and Cambridge (1984)
Posidonia kirkmanii	6–18	Kuo and Cambridge (1984)
Amphibolis antarctica	0.1–27.3	Walker and McComb (1988), Shepherd and Womersley (1981)
Amphibolis griffithii	0.5–44	Shepherd and Womersley (1981) Huisman et al. (1999)
Thalassodendron pachyrhizum	2–48 m	Kirkman and Cook (1987) Huisman et al. (1999)

Information Box: Deepwater Seagrasses in Temperate Southern Waters

Seagrasses have wide depth distributions in south and south-western Australia, and extreme depth records occur in very clear oceanic waters with low light attenuation on the continental shelf of temperate Australia (Duarte 1991; Gattuso et al. 2006). These deep-water seagrass communities are heavily influenced by availability of hard substrata (to anchor within) and by significant wave height and benthic shear from ocean swells and currents (Hemer 2006).

A survey of the taxonomic and distribution literature (Table 3.2) indicates that most species found in temperate Australia have been reported from a broad range of depths. The *Posidonia australis* complex is generally found in sheltered bays and estuaries with species that are predominantly sheltered and shallow water (<15 m) in distribution (*P. australis*) and species that are predominantly exposed coastal and offshore deep water adapted (*P. angustifolia*) (Cambridge and Kuo 1979). The *P. ostenfeldii* complex are predominantly all deepwater species with distributions well beyond 15 m and restricted in distribution to sheltered bays to open ocean environments (Kuo and Cambridge 1984). *Heterozostera*, *Amphibolis* and *Halophila* species are found in sheltered estuarine and coastal environments but occur in the open ocean to 40 + m depths (Shepherd and Womersley 1981; Shepherd and Robertson 1989). *Thalassodendron pachyrhizum* is predominantly a deep-water species but can be found in shallow waters where benthic shear from swells is high. It has been reported to form extensive meadows at 35 m and greater depths (Kirkman and Cook 1987). Our knowledge of temperate deepwater seagrass communities is restricted to broad habitat information and occurrence and little research has characterised seagrass distributions and seagrass adaptation to deeper, more wave exposed environments.

Recent remote surveys using video and hydroacoustic methods have expanded our knowledge of distribution and in this section we will present data about seagrass distribution from Recherche Archipelago from extensive video tows. Also we will propose that *T. pachyrhizum* is a deepwater seagrass and present data from drop video surveys of Cape Naturaliste, as well as deeper and remote continental shelf environments west of Jurien, Western Australia.

The inshore continental shelf near Esperance, Western Australia encompassing the western Recherche Archipelago from Figure of Eight to Mondrain Islands, was recently mapped (Kendrick et al. 2005) and one of the major surprises was that seagrasses were not restricted to sheltered inshore environments but found subtidally near islands greater than 30 km offshore and at depths to 50–60 m. An extensive database allowed for the depth distribution of major seagrass genera to be determined (Fig. 3.8). For the genus *Posidonia* the average depth across all 7 species observed was 16.7 ± 7.4 m (mean ± SD, n = 692) and a maximum recorded depth of 37 m. For the genus *Amphibolis* (*A. antarctica* [rock] and *A. griffithii* [sand]), the average depth was 19.9 ± 8.9 (mean ± SD, n = 175) and a maximum recorded depth of 51 m. For the genus *Halophila* (predominantly *H. ovalis* and *H. australis*) the average depth was 22.4 ± 8.3 (mean ± SD, n = 282) and a maximum recorded depth of 49 m. The average depth for all genera are greater than the criteria used to define deep-water seagrass communities in tropical Australia (Coles et al. 2009) where only *Halophila* species are present deeper than 15 m. The diverse mix of temperate seagrass species found at depth in the waters of Esperance demonstrates the link between water clarity and seagrass depth distributions as originally summarized by Duarte (1991) and later modelled by Gattuso et al. (2006).

Thalassodendron pachyrhizum is a species that occurs predominatly in deeper waters on the continental shelf or wave swept shallower waters nearer the coast. Preliminary research on leaf production, biomass, reproduction and the production of viviparous seedlings indicates it is well adapted to deeper low light, high wave energy mid- to outer continental shelf environments (Kirkman and Cook 1987; Kuo and Kirkman 1987). Drop camera surveys were undertaken at Cape Naturaliste across depths from 15 to 60 m and at the

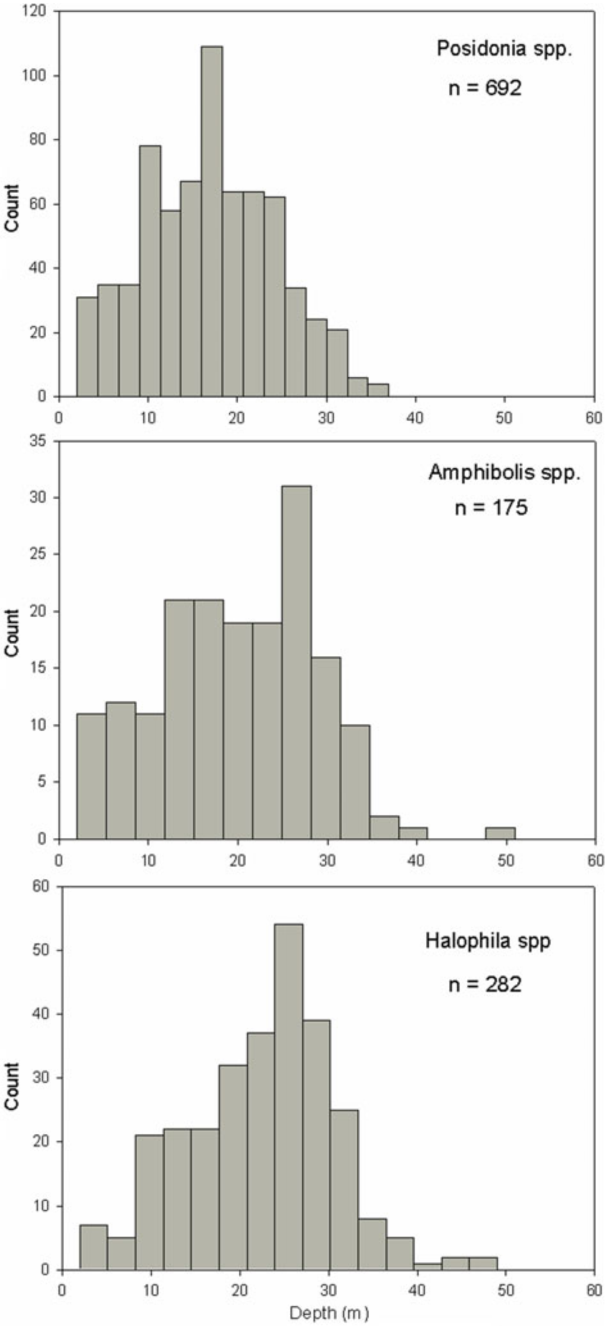

Fig. 3.8 Frequency histograms of depth distribution of major genera of seagrass found in the western Recherche Archipelago (Data from Kendrick et al. 2005)

edge of the continental shelf >30 km west of Jurien Bay in 25–70 m depth, during 2008 as part of a National Heritage Trust II project 'Securing WA's marine futures' (Radford et al. 2008). Surveys on limestone and granite reefs at Cape Naturaliste found the average depth where *T. pachyrhizum* occurred was 33.8 ± 5 m (mean ± SD, n = 55) with a maximum recorded depth of 43.5 m. Surveys on the limestone reefs at the edge of the continental shelf found the average depth where *T. pachyrhizum* occurred was 35.3 ± 3.5 m (mean ± SD, n = 140) with a maximum recorded depth of 49 m. The survey extents were 166 km^2 for Cape Naturaliste and 72 km^2 for Jurien. The coverage of seagrasses was patchy but extensive, suggesting these meadows are ubiquitous across these depths on sand covered limestone reef and pavement on mid to outer shelf oceanic environments. Their role and importance in the deep shelf environments is presently unknown. Similar deepwater collections have been made for many of the seagrasses in southern Australia indicating deepwater seagrass meadows are ubiquitous although patchy in distribution across much of the continental shelfs of temperate Australia.

3.4 Impacts on Seagrasses in this Region

The major threats to seagrasses are coastal development, eutrophication, extreme climate events and global warming. Over the last two decades, the loss of seagrass from direct and indirect human impacts amounts to 18% of the documented global seagrass area (Green and Short 2003).

In Western Australia, significant areas of seagrass have been lost in protected coastal embayments (Table 3.3). The most well documented anthropogenic loss of 1000s of hectares of seagrass is Cockburn Sound. In the 1950s and 1960s, the seagrass species *Posidonia sinuosa*, *P. angustifolia* and *P. australis* formed an almost continuous meadow between 1 and 10 m depth that fringed the eastern, southern and western coasts of the sound. Over 5 years, between 1967 and 1972, 1587 ha of seagrass meadows were lost from the eastern and south-eastern shallow shelfs (<10 m depths) of the Sound (Cambridge and McComb 1984). The decline in area of seagrass cover was driven by nutrient inputs from sewage, a fertiliser plant and other industrial effluents (Cambridge et al. 1986; Kendrick et al. 2000, 2002). The significant quantity of dead seagrass leaf and rhizome material that entered detrital pathways from the seagrass loss (Cambridge and Hocking 1997), over extensive areas of the eastern and southern fringing shelves fuelled the conversion of the inshore ecosystem from net autotrophic to net heterotrophic. Losses of seagrasses continued into the 1980s and early 1990s. Loss through dredging and land reclamation has also occurred in Cockburn Sound, Albany harbours and Esperance Bay, but the scale of direct impact is in the 10s to 100s of ha (Table 3.3).

Table 3.3 Drivers of seagrass decline and scale of seagrass response in the SW of Australia

Authors	Location	Spatial extent	Driver	Response
Hastings et al. (1995)	Rottnest Island, Western Australia	81 ha	Mooring and anchoring of boats	Rocky Bay loss of seagrasses total 31% 18% 1941–1981 13% 1981–1992 Thomson Bay 1941–92 < 5% Fragmentation occurring but seagrass recovery fast
Kendrick et al. (2000)	Success and Parmelia Banks, West. Australia	3,974 ha	Channel dredging, limesands dredging, nutrients	Between 1965 and 1995 there was a 21% increase in seagrass cover on Success Bank. On Parmelia Bank % cover of seagrasses has remained constant at approx 45% Seagrasses responsible for gains are *Amphibolis griffithii* and *Posidonia coriacea*
Seddon et al. (2000)	Spencer Gulf, South Australia	8,269 ha	Extreme low tide and warming of nearshore waters	Historical dieback between 1987 and 1994 in the intertidal and shallow subtidal Over 8269 ha showed dieback attributed to climate change associated with El Niño
Kendrick et al. (2002)	Cockburn sound, Western Australia	3,667 ha	Eutrophication	Historical decline in seagrass area by 77% since 1967. 1967–72: 1587 ha lost. 1972:1981: 602 ha lost. 1981–1999: 79 ha lost. Species of seagrass lost were predominantly *Posidonia sinuosa*
Bryars et al. (2003), Bryars and Neverauskas (2004)	Adelaide waters, South Australia	365 ha	Nutrients, smothering and reduced light	Loss of seagrass in area near sewage outfall. Recovery was slow and dominated by *Halophila australis*
Hegge and Kendrick (2005)	Esperance Bay	773 ha	Port infrastructure, dredging and land reclamation	Between 1956 and 2001 83 ha were reclaimed, 72 ha were dredged resulting in in the loss of 116 ha of predominantly *Posidonia sinuosa* meadows
Bryars and Rowling (2009)	Eastern Gulf of St Vincent	>2,000 ha	Wastewater treatment plant outfalls (and thus elevated nutrients)	Selective disappearance of *Amphibolis* in three distinct areas since the 1930s, with loss in one area (Henley Beach to Brighton) estimated to be 1,000–2,000 ha

Indirect impacts from dredging have only recently been addressed (Fraser et al. 2017) and the extent of combined indirect and direct effects is generally underestimated. Mooring and anchor damage has also been reported at Rottnest Island near Perth with combined losses from many mooring in the range of 10s of hectares, predominantly driven by physical scouring of the bottom by chains. The largest recent losses of seagrasses in Western Australia were driven by a marine heatwave in 2011 (1,000s of km^2: see information box *Climate Change—increases in extreme events*) and subsequent synergistic interactions, with light availability from floods and increased turbidity associated with microbial breakdown of seagrass biomass, that continued to drive seagrass loss for over 2 years.

In South Australia, most reported loss of seagrass meadows has been linked to increased nutrient inputs and subsequent synergistic interactions with associated sediment destabilisation. Approximately 5,000 ha of seagrasses were lost over 70 years from the metropolitan Adelaide coastline in eastern Gulf St Vincent. The initial loss was linked to wastewater treatment plant outfalls and stormwater discharges, and subsequent loss associated with increased sediment mobilisation and local erosion (Westphalen et al. 2004). Approximately 168 ha of seagrass were lost near Port Lincoln in southwestern Spencer Gulf due to declining water quality including discharge wastes from fish processing factories (Hart 1999; Gayland 2009). Similarly, significant losses of subtidal seagrasses reported in Western Cove on Kangaroo Island were linked to eutrophication due to land-based nutrient inputs (Bryars et al. 2003), as was the disappearance of large areas of deepwater *Heterozostera* over a 30-year period in Investigator Strait/Gulf St Vincent, where losses may have been due to land-based discharges and prawn trawling (Tanner 2005). Also, other activities reported to have impacted seagrasses include mining and seismic operations, construction works, aquaculture structures, and moorings (Shepherd et al. 1989; Madigan et al. 2000; Bryars 2003; Bryars et al. 2003). Large-scale natural losses of intertidal and shallow subtidal seagrasses (up to 13,000 ha) in northern Spencer Gulf were linked to extreme weather conditions (Seddon et al. 2000). The spatial scale of loss from climate and oceanographic events like the Spencer Gulf and Shark Bay examples described here are generally much greater (1,000s of ha to 1,000s of km^2) than those associated with direct anthropogenic impacts, and the combined impacts from multiple stressors at the ecosystem scale, like those in Cockburn Sound and Adelaide waters pose the greatest threat to temperate seagrasses in in western and southern Australia.

Information Box: Climate Change—Increases in Extreme Events

Shark Bay Seagrass Defoliation—Marine Heatwave of 2011

In summer 2011, the west coast of Australia was affected by a marine heat wave that elevated sea temperatures 2–4 °C higher than normal over several weeks, resulting in coral bleaching, macroalgal mortalities, and fish kills over much of the coast (Wernberg et al. 2013). In Shark Bay, temperate species, *Amphibolis antarctica* and *Posidonia australis* are the dominant seagrasses, although they are towards the northern limits of their geographical distribution. Tropical species of the genera *Cymodocea*, *Halodule* and *Halophila* are found growing with these temperate species.

Defoliation of *A. antarctica* meadows was observed baywide but was more extreme in areas of high turbidity, driven either by detrital pools across the whole Shark Bay System as well as riverine particulates in floodwaters from the Wooramel River. *A. antarctica* was susceptible to decreases in light availability when combined with higher temperatures, presumably due to increased respiratory demand with no ability to increase photosynthesis to match (Walker and Cambridge 1995). The small, tropical seagrass species, *H. uninervis* was unaffected by the combined flooding and warming event as it is adapted to higher water temperatures. In addition, high seed production and dormancy in the sediments in this seagrass would be well suited to increases in frequency and intensity of disturbance events like marine heatwaves and riverine flooding.

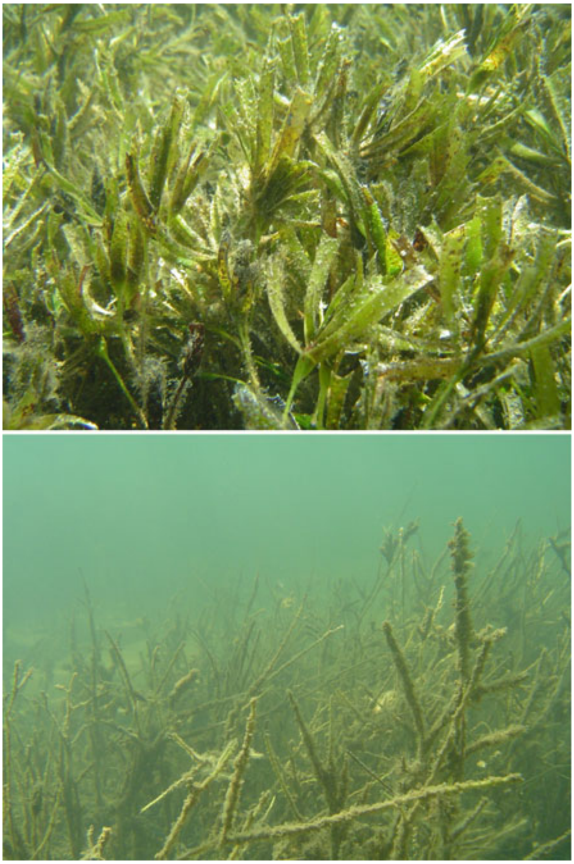

Fig. 3.9 Healthy meadows of *Amphibolis antarctica* in Shark Bay (top) and defoliated meadow after 2011 marine heatwave (bottom) on the Wooramel Bank, Shark Bay Western Australia

In the eastern gulf, defoliation of *Amphibolis antarctica* increased with proximity to floodwaters originating from the Wooramel Delta (Fraser et al. 2014). In March, two months after the combined effects of high water temperatures generated by the marine heatwave 2011 and flooding from extreme weather, plants were either totally or showed a high level of defoliation within 15 km of the Wooramel river mouth (Fig. 3.9) and plants subsequently died. Above-ground (leaf) biomass 2 years later was only 7–20% of that recorded before the 2011 marine heatwave.

Similarly, in the L'Haridon Bight, Monkey Mia and Peron Peninsula meadows, wide-scale defoliation of *A. antarctica* and death of meadows was clearly observed 1 year after the marine heatwave. Percent cover of *A. antarctica* declined from median values of 65% to less than 10% in L'Haridon Bight (31 sites), 80% to <10% in sites at Monkey Mia (42 sites), 65% to <5% on the eastern Peron Peninsula (20 sites), and 65–25% on the eastern Peron Peninsula including Denham (20 sites) (Thomson et al. 2015).

Defoliation of *A. antarctica* was a bay-wide phenomenon. The greatest effects were seen in shallow areas nearshore, at depth, and in turbid waters. The loss of a major foundation species across such a wide region in Shark Bay has already affected seagrass dependent marine organisms with a decline in health status of the herbivorous green sea turtle, *Chelonia mydas*, evidence that there were long-term community-level impacts to Shark Bay from the marine heatwave (Thomson et al. 2015).

The other major seagrass, *Posidonia australis* did not show defoliation across the bay, but 100% seed abortion was observed from flowering in the Western Bay and Peron Peninsular (Sinclair et al. 2016). Flowers developed pericarp (fruit) but these were all empty, containing aborted embryos. Successful reproduction has only recently been observed in 2016.

Given the ecological importance of *A. antarctica* in Shark Bay, accounting for 85% ($\sim$3700 km^2) of the total cover of seagrasses (Walker et al. 1988), predicted increases in the frequency and magnitude of marine heat waves and floods will have catastrophic implications for these seagrass ecosystems at the northern extremes of their distribution. Also, a recent assessment of tropicalisation of temperate and tropical seagrasses ecosystems along the Western Australian coastline predicted that the temperate seagrasses *A. antarctica* and *P. australis* would contract in geographical distribution southward between 200 and 400 km by 2100 (Hyndes et al. 2016). Although this range contraction prediction is limited as it based only on published physiological optima and limits in temperature for these seagrasses, and thus did not take into account acclimation and adaptation to higher temperatures in these species, it does give a dire early warning of the future for temperate seagrasses that are already at their range limits.

3.5 Emerging Threats and Management Issues

With coastal development, eutrophication, extreme climate events and global warming, seagrasses in this region face a future of risk from multiple stressors at the ecosystem scale. The anthropogenic threats which have been responsible for many of the reported cases of localised seagrass loss are shown in Table 3.3. We expect increased human development of the coastal zone and associated effects of overfishing, physical destruction, and seagrass loss from eutrophication, increased turbidity, and other pollutants to continue to be a risk to seagrass in this region, however it is now combined with climate-related changes which have the potential to affect very large areas. Seagrasses exposed at low tide may be threatened by climate change (c.f. Seddon et al. 2000) and sea-level rises, particularly if hardening of coastlines occurs to protect infrastructure. Climate change also will bring changes in the frequency, seasonal timing and severity of storms and storm surges that threaten to physically remove seagrasses from shallow subtidal coastal areas. Estuarine seagrasses may be lost in some areas due to reductions in freshwater flows associated with climate change. Subsequent increases in salinities associated with evaporation in some shallow systems may be beyond the physiological tolerances of seagrasses (as already observed in The Coorong).

Invasive pest species, including *Caulerpa taxifolia* and *C. racemosa* that are already established in the Port River region of eastern Gulf St Vincent, South Australia, and may threaten seagrasses as documented in other parts of the world (De Villèle and Verlaque 1995). *C. racemosa* has also been observed within seagrass beds in the Leschenault Estuary, Western Australia (Department of Water and Environmental Regulation, unpublished data).

Disturbance of the natural hydrological and detrital cycles, through coastal development and construction of marinas, has been a realised management issue in the last decade in Western Australia. The highly productive seagrass meadows of Geographe Bay, and the annual detritus they produce, caused a significant management issue following the construction of Port Geographe. Breakwaters which were designed to prevent sand bar formation at the harbour entrance, actually became a very efficient trap of seagrass wrack (estimates of 100,000 m^3, several metres high and 1–2 km in length) (Pattiaratchi et al. 2015). Loss of beach access and hydrogen sulfide generated from decaying seagrass wrack caused issues for local residents. The breakwater, seawall and entrance channel were eventually reconfigured at a cost of $28 million in 2015 to address the problem caused by the initial development (http://www.transport.wa.gov.au/portgeographe).

3.6 Summary

The southern and southwestern Australian marine environment is a region of unique biodiversity. The future of seagrasses in this region depends more than ever on smart and effective management preventing the impacts of major and emerging threats. Other than the loss of seagrass due to coastal development, the greatest threat to temperate seagrasses of this region is from climate and oceanographic events, such as heat waves. Indeed these climate associated losses occur at spatial scales that surpass those of the direct anthropogenic impacts. However, the future for effective management of seagrass is also brighter than ever, with increased understanding of recruitment bottlenecks, restoration options and aspects of seagrass resilience.

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